Geomorphological Field Guide Book

on

CHAMBAL BADLANDS

By

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Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
Geomorphological Field Guide Book on
Chambal Badlands

Itinerary

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A. CHAMBA L BADLANDS: AN INTRODUCTION

Land degradation is considered to be one of the most severe global environmental challenges (Eswaran et al., 2001; Lal, 2001; Scherr and Yadav, 2001). It has numerous economic, social and ecological consequences. Land degradation is also an important geomorphic process in many parts of the world and in a range of landscapes. Its causal determinants, in terms of local specificities, are yet to be understood fully (Lambin et al., 2003, 2009). Gully initiation and evolution, like many other processes of land degradation, has been attributed to diverse natural and anthropogenic causes (Burkard and Kostaschuk, 1995; Dregne, 2002; Wells and Andriamihaja, 1993). Natural causes of ravine erosion include climate change (Poesen et al. 2003), catastrophic storms, and isostatic rebound, tectonic uplift or base level lowering (Begin et al., 1981; Ouchi, 1985). Removal of vegetation and deforestation (Bensel, 2008; Ireland et al., 1939; Quiggin, 2009; Singh and Agnihotri, 1987), overgrazing (Quiggin, 2009; Wells and Andriamihaja, 1993), population pressure, institutional settings and public policy (Blaikie, 1989; Boardman and Poesen, 2006; Anand and Herath, 2003; Stocking and Murnaghan, 2001) are among the significant anthropogenic factors causing land degradation (Pani and Carling, 2013).

The Chambal Badlands (26°17′15″ to 26°52′22″N, and 76°28′30″E to 78°32′55″E) occurs within the catchment area of the Chambal River that originates from the Vindhyan Ranges in the Indian Peninsula, and is one of the most degraded areas in India (Fig. 2). It occupies 4989 sq. km area in the states of Uttar Pradesh, Madhya Pradesh and Rajasthan. Much of the badlands in the visit area have developed in the catchments of the Chambal River flowing in SW to NE direction and its tributary, the Kunwari River, which flows from south to north and then northeast and meets the
Chambal on its right bank. The deep networks of gullies developed here are known for their ruggedness and high inaccessibility. It is also infamous for centuries for the outlaws. We provide here a short overview of the physical and cultural aspects of the area.

**Physical Features of the Area**

**Climate**

The area falls within the limits of the semi-arid and the sub-humid regions. Moderate rainfall, high temperature, dry summer and cold winter are the main features of climate here. The three main seasons are summer (March-June), rainy (July-September) and winter (October-February). Summer is mostly dry and hot, when the mean maximum temperature rises to 42°C in May, but the winter is mild, with a mean minimum of 7°C in January, although it is not uncommon to experience >45°C during summer and 1-3°C during winter. The mean annual rainfall varies from 765 mm at Agra to 796 mm at Morena, while Delhi to the north of the area receives 714 mm annually and Gwalior at the south receives 900 mm. Much of the rainfall is received during July-September, the season for summer monsoon rains, when about 90% of the total annual is received.

**Geomorphology**

The route from Delhi to Agra and from there to Morena-Bhind area falls within the vast Ganga Plains (Fig. 3). The area from the foothills of the Himalayas to the lower Chambal valley near Gwalior can be broadly subdivided from north to south into three geomorphic units: (1) Piedmont Zone (PZ), (2) Central Alluvial Plain (CAP), and (3) Marginal Alluvial Plain (MAP) (Agarwal et al., 2002; Goswami and Mishra, 2014; Singh, 1996). The landform units in the area can be grouped under three genetic types, viz. fluvial, denudational and structural origin. Landform units of fluvial origin are the alluvial plains, flood plains, river terraces, ravinous zones and valley fills. Landform units of denudational origin include the residual hills and buried pediments, while the landform units of structural origin include the mesa, buttes and plateaus. The alluvial plains cover almost fifty percent of the area.
Chambal River is a major tributary of the Yamuna that originates from the Himalayas. The ravines are formed on both sides of the Chambal River and its tributaries. The total basin area of the Chambal River is about 143219 sq. km. The average gradient of the river in lower Chambal valley is 0.21m/km (Jain et al., 2007). The main tributaries of the Chambal are the Chamla, Kshipra, Kalisindh, Mej and Parvati. The Chambal serves as a major source of hydro-electric power generation, irrigation and fisheries for Madhya Pradesh and Rajasthan States.

A major part of the visit area in Morena-Bhind tract is under a thick alluvium deposited by the Chambal River and its tributaries (Fig. 3). The area of interest, the Badlands, come under the Marginal Alluvial Plain, which is enclosed by the Yamuna River and the Indian craton, where the land is characterized by an intricate network of gullies along the Chambal, the Betwa and the Yamuna Rivers as well as along their tributaries (Ranga et al., 2015a).

Chambal Badlands are extremely dissected, difficult to cross and is agriculturally unfit. The area between Bhind and Morena is the most dissected, with an irregular topography, and consists of steep ridges, low hills, deep trenches and broad incised meanders (Fig. 4). The area is also dotted with small hillocks of Vindhyan sedimentary formation within the Chambal Valley and its ravines, which are separated from the main expanse of the Vindhyan Range. A number of isolated hills are scattered also in the alluvial tract. Limestone and sandstone constitute the residual hills having moderate relief of the order of 240-260 m.
Fig. 4. ASTER DEM (30 m) to show the rugged topography of the Chambal Badlands. Box shows the Morena-Bhind area.

Fig. 5. A gully in the foothills.
Badlands in the lower Chambal valley have incised a former active floodplains (which is now inactive), and have formed a narrow valley. Steep ridges, low-sloping hills, deep trenches and broad meanders are common features of the area (Fig. 5). The general slope of the area is towards north-east (Pani and Carling, 2013). Steep scarps form the boundary between the badlands and the adjacent inactive flood plain (Fig. 6). At many places leveling activities on such scarps can be noticed, where the boundary becomes vague and land use becomes transitory (Ranga et al., 2015b). The active flood plain is restricted to the narrow incised valley, marked by point bars on the concave curves of meanders, which are formed by meander cut-off and lateral migration of the river. The palaeo-channels are all observed in the inactive floodplains which are now used for cultivation purpose (Ranga et al., 2015a).

Apart from the Chambal, the main river flowing in the Badlands area to be visited is the Kunwari River (Fig. 7). It emanates from the Vindhyan Hills in Shivpuri district of Madhya Pradesh, and then flows in north-east direction through the Vindhyan scarps in Bijaipur, Jora, and Sabalgarh tehsils. This river is the major source of fresh water supply in the area. When it enters the Morena plain, it forms deep ravines and wipes out much of the nutrients of the plain (Singh, 1978). The river flows through a hilly tract and joins the Chambal River. The drainage pattern is mostly dendritic to sub-dendritic. All rivers generally flow from south to north or north east and meet the Chambal River on its right bank. Drainage density is high in the valley portion and in the plains.

Fig. 6. A steep scarp between the badlands and the Chambal River.

Fig. 7. ASTER DEM (30 m) of the ravines along the Chambal River and its major tributaries near the Chambal-Yamuna confluence.
Soil

Soils of the lower Chambal valley vary widely. In the soil map of India, the Lower Chambal Valley falls within the limits of two main soil groups, viz., the reddish grey and the yellowish brown alluvial soil. In general, the soils have a surface colour of pale brown to yellowish brown with patches of greyish tinge. In the visit area the soils are broadly of two types: (i) sandy loam to loam with low phosphorous and salt content, and (ii) clayey loam with low phosphorous and salt content (GoMP 1996; Pani and Carling, 2013).

Vegetation

The natural vegetation consists of various kinds of thorny, shrubs and trees, including Berry, Dhou, Kardhai, etc. The forest mostly comprises of small thorny bushes not consisting of any thickly grown trees, except in some parts of the valleys. However, in some parts of Tonga, Mala and Navez valleys taller trees of Dhau, Mahua, Jamun, Palas (Tesu), etc., are also present. The ravine land is generally devoid of a good vegetation cover. The predominant species in ravine area are mostly Anogeissus pendula. The significant minor forest products are Tendu (Diospyros melanoxylon), Khair (Acacia catechu) and Harra (Terminalia chebula).

Socio-economic Aspect

The historical records related to the area can be traced to the ancient time. Although there are scanty historical records to indicate when ravine erosion became noticeable, Habib (1963) designated badlands in India as a pre-Mughal phenomenon (i.e., before 1526 AD), but no historical records were found to trace their formation (Singh & Agnihotri 1987). The Chambal administrative division is densely populated, and a large section of the population lives in rural areas. Although the inhabitants of Chambal area belong to multiple religions and castes, the word Chambal has become almost synonymous with dacoits. Dacoity would not have gained such anchorage here, but for the favourable geographical/terrain conditions. The intricate gully networks, the ruggedness of the topography, and the least opportunity for agriculture in an undulating dry terrain have all helped the dacoits a safe heaven away from the glare of the law.

The sprawling ravines indeed make for excellent hideouts. The socio-economic reasons include a high density of rural population in the plains surrounding the badlands and within it in small patches, that dominantly depend on subsistence agriculture, increased fragmentation of land holdings over time as the population rises, inability to spread cultivation into the badlands area or to gainfully utilize that vast barren land for agriculture, non-availability of other employment opportunities and adequate infrastructures, as well as a sense of isolation. Frequent droughts were also a factor to coop with. The region has a long history of droughts that make rain-fed cropping somewhat uncertain. Occasionally excessive rains also lead to crop loss and food shortages (GoMP, 1996). Despite this, the rural poverty in Morena is less than expected.

Fortunately, situation started to improve gradually since the 1970s when a series of development activities were undertaken to improve the land condition, to provide infrastructural and other facilities, and to help the inhabitants in getting a better return from the resources available. Now the problems of dacoity are almost non-existent.
A sample survey in several villages has revealed that about 80% of the inhabitants depend on cultivation and dairy, while the rest are mostly carpenters, weavers, agricultural labours, wage earners, etc. Most of the families are of middle-income group. Literacy rate is, however, low (38%). As against the rural head-count poverty of 37% in Madhya Pradesh, the poverty in Morena was 21% in 2004-2005, while the urban poverty ratio was 42%, which was almost at par with the state’s urban poverty of 43% (Chaudhuri and Gupta 2009; GoMP 2007; Pani and Carling, 2013).

The medical facilities were very few in the area till recently. Only a few dispensaries used to run by the State Government; so the people had to depend more on traditional medicines. The situation is now gradually improving. Low literacy level of the families has been responsible for a general lack of awareness about sex education and child health care.

About 80% of the families, though, have some knowledge about ravines and their formation, types and reclamation. These people are quite aware that the ravines affect the fertility of the soil. As infrastructures, canals, and services have started to link the area with other neighbouring areas, vast changes have started to take place in the socio-economic fabric of the area.

**Major Land Uses:** Of the gross cropped area, food crops accounted for 55.65%, and non-food crops account for 44.35% of the area in 2007–2008. During 2005-2008 nearly 66% of the net shown area was under irrigation. Canals, tube wells and wells are the main sources of irrigation in the area. Canal irrigation is a recent phenomenon in the area, and includes two canals, the Morena Branch Canal and the Ambah Branch Canal. During the pre-canal period wells were the major source of irrigation, and irrigated area was highly restricted. With the construction of the Chambal Main Canal, on an average 17933 ha of land is now irrigated every year. Rain-fed agriculture in the region is characterized by low productivity and low levels of marketable surplus.

Badlands along the lower Chambal valley are now getting levelled manually (Fig. 8). The use of tractors and bulldozers has transformed some parts of the badlands as a rolling topography. Completely or near-completely flattened land is normally found either in the sufficiently wide valley bottoms within the badlands or in the remnants of the dried channel meanders. The more undulating levelled lands are the work of tractors or bulldozers, with clear signs of scouring (Ranga, 2013; Poesen et al., 2006).

The question of sustainability of agriculture here, as elsewhere, mainly focuses on production over an extended scale of time and space. This essentially would mean that crop production and economic gains would flourish over a long period of time, almost infinitely and globally (Shah, 2006). It encompasses a range of strategies for addressing many of the problems such as loss of productivity from excessive erosion and associated plant nutrient losses, surface and groundwater pollution from pesticides, fertilisers, and sediments, impending shortage of non-renewable resources, and low farm income from depressed commodity prices and high production cost (Parr et al., 1990). Moreover, agricultural sustainability implies a time dimension and the capacity of a farming system to endure indefinitely (Lockeretz, 1988; Kumar and Pani, 2013).
Fig. 8. Land levelling for cultivation in the badlands area.
B. DESCRIPTION OF THE FIELD SITES

Day 1
Arrive at Agra
Stay at Agra

The day will be spent in discussing the details of the visit and in sight-seeing in and around Agra.
In order to appreciate the badlands landscape in next two days, a review of badlands formation and control measures is provided below.

Badlands Characteristics, Processes and Control Measures

Among the diverse types of land degradation in India, ravine is one of the severe forms, where the loss of top soil has major economic implications. There are four major ravine zones in India: the Yamuna-Chambal ravine zone, the Gujarat (Tapti, Narmada, Sabarmati, Mahi) ravine zone, the Chota Nagpur ravine zone, and the Shiwalik Foothills (Punjab) ravine zone. Of these four zones, the Yamuna-Chambal ravine zone is the largest (Sharma, 1980), and the badlands along the Chambal and its tributaries are the most severely incised and degraded (Sharma 1979). The adverse effects of the ravine erosion in the lower Chambal valley go far beyond the removal of valuable topsoil on which plants depend for their nourishment. The direct effects include gradual decline in crop yield and engulfment of agricultural land by ravines. Thus, the proximate impacts of ravines are highly concentrated in agriculture. In some cases, these impacts are so intense that farmers have to shift their settlements (Pani and Mohapatra, 2001b). Further, the spill-over effects of gully erosion gradually impinge on the livelihoods of people in varying ways (Pani, 2012). The interrelationship between economic processes and land degradation in this region, like elsewhere, is multilevel and complex.

Gullies are formed due to localized surface runoff affecting unconsolidated terrain. Initially gullies are emerged from rills, which are few centimetres deep. Regardless, after impact of heavy rainfall and wearing action of runoff, its size of degradation increases (NRSC, 2011). Majorly Madhya Pradesh, Chhattishgarh and Jammu & Kashmir states are sevry affected by the ravines problem. In 2008, Morena (MP), Bilaspur (Chhattisgarh) and Rajauri (J&K) had more than 5% degraded land of their total geographical area (TGA) affected by gullied and ravines. In 2005, the number of degraded districts with >5% under ravines was more than in 2008: Morena, Bhind in MP, Rajauri, Pulwama in J&K, Bilaspur in Chhattisgarh, Bundi in Rajasthan, and Chandigarh in Punjab (Priya and Pani, 2015).

Characteristics of the badlands: Badlands are characterised by highly dissected topography with steep slopes where inter-rills, rills, gullies and ravines form integral parts. The different types, such as deep ravines (Fig. 9), moderate gullies (Fig. 10) and shallow gullies (Fig. 11), can be identified in the Chambal Badlands area. The advancement of the gully networks takes place especially through headward erosion of individual gullies (Fig. 12). Various stages of formation of the ravines in the area can be summarised into (a) swallow hole stage (Fig. 13), (b) piping stage (Fig. 14), and (c) collapsing stage (Fig. 15).

Being an agriculture-dependent economy, India suffers great economic loss to badlands (Ranga et al., 2015b). The lower Chambal valley accommodates badlands covering an area of about 4800 sq. km (Sharma, 1979). Initiation and formation of badlands are considered
to be an effect of Himalayan orogeny (Ahmad, 1968; Sharma, 1968; Agarwal et al., 2002) and probably also due to intensification of southwest monsoon between 15–5 ka ago (Gibling et al., 2005). Due to Himalayan orogeny, the fore-bulge of Himalayan foreland basin (Gibling et al., 2005; DeCelles, 2011) experienced an uplift (Agarwal et al., 2002) which forced the Chambal River to attain a new equilibrium. On attaining the new equilibrium, the Chambal River incised into its own deposited sediments and in the due process, badlands, on both sides of the Chambal River, came into existence (Sharma, 1979; Pani and Mohapatra, 2001, Poesen et al., 2016).

![Fig. 9. A deep ravine in the Chambal Badlands.](image)

![Fig. 10. A moderately deep gully in the Chambal Badlands.](image)

Considering the significant contribution of agriculture to economics, the focus of badlands studies was always on reclamation with Government of India (GoI) support. Early known attempts to assess badlands encroachment were made by Sharma (1979), who used Survey of India (SOI) topographic sheets, field observations and interviews with local farmers to map the badlands. He found badlands encroachment rate varying from 20 to 40 cm per year. Later, Haigh (1984) suggested that India’s badlands continued to expand at the rate of 1% per decade. In the subsequent years, GoI (1996; as cited in Deshmukh et al., 2011) reported a reduction in areas covered by badlands from 3.97 million ha in 1971 to 2.67 million ha in 1996. However, this reduction figure of about 33% was severely criticised by Deshmukh et al. (2011) who suggested that the approach was mere in-room discussion and
lacked ground survey. Recent publications still suggest that badlands are encroaching into the croplands, engulfing fertile land and thus posing a great threat to the regional economy (Pani and Mohapatra, 2001; Joshi 2014; Poesen et al, 2016).

Fig. 11. A shallow gully in the Chambal Badlands.

Fig. 12. Headward erosion of a gully in the Chambal Badlands.

Fig. 13. Swallow hole stage of badlands formation.

Fig. 14. Piping stage of the badlands formation.

Fig. 15. Collapsing stage of the badlands formation.
**Process of formation:** Badlands fascinated dissected topography, unconsolidated soils or poorly consolidated bedrock for the same reasons that inhibit agricultural uses, like lake of vegetation, steep slopes, high drainage density, shallow to non-existent regolith and rapid erosion rates (Bryan and Yair, 1982; Howard, 1994; Poesen et al., 2003). Such areas are commonly affected by intense processes of soil erosion, including gulling, rilling, and sheet wash erosion (Nadal-Romero et al., 2008, 2010; Shit et al., 2013). Gullying is one of the most important erosion processes, largely contributing to the sculpturing of the earth surface over the last decade. The advancement of gullies has many pessimistic impacts as it usually engrosses the loss and the deposition of a great amount of soil (De Ploey, 1990; Marzolff et al., 2011). Moreover, the development of gullies entails an amendment of overland flow, shortening of runoff lag time and an increase in runoff volume. Many efforts have been made to understand the main factors and processes of gully formation (Boardman, 2006). Deforestation played a major role for gully erosion in developing countries. Removal of vegetation by logging or cropland spreading out in humid areas, or by overgrazing in semiarid zones, favours the advancement of gullies (Bull and Kirkby, 2002; Marzolff et al., 2011). Gullies perhaps develop through different, concurrent factors. Poesen et al. (2003) stated that inter-rill flow tends to concentrate downslope into pathways leading to a more efficient flow and to a decrease in flow resistance. It follows that the interaction between overland flow and ground surface roughness is a process relevant to gully initiation (Poesen et al., 2006; Govers et al., 2007; Campo-Besco et al., 2013). Expansion of gully continues being influenced by flow resistance and morphological characteristics of the features (Ries and Marzolff, 2003; Seeger et al., 2009; Shit et al., 2014).

**Causes of formation in India:** In India, ravine erosion is one of the prominent processes of land degradation. Recent literature has focused on ravine mapping and classification using optical and high-resolution remote sensing data (Sujatha et al., 2000; Dwivedi and Ramana, 2003; Chatterjee et al., 2009; Pani and Mohapatra, 2001b). These studies emphasized deforestation, overgrazing and unsuitable farming practices as causes of gully erosion (Sharma, 1980; Haigh, 1984; Singh and Agnihotri, 1987; Pani and Mohapatra, 2001a, 2001b). Gully erosion gets further aggravated due to the intensity and concentration of rainfall during the monsoon, as well as due to the erodibility of the thick alluvial soils where most of the ravines develop (Sharma, 1980). Specifically, the relative significance of climatic factors in ravine formation in India has been a source of debate (Haigh, 1984; Pani et al., 2005). Most of the studies favour multiple combinations of socio-economic and biophysical factors rather than any single set of factors responsible for ravine formation (Sharma, 1980; Pani et al., 2005; Pani et al., 2011; Pani and Carling, 2013).

**Control measures:** Regional vegetation knowledge can be very useful in effective control of soil erosion through aerial seeding in Chambal valley. Adams (1987), on finding the seeding effort being ineffective, suggested grass buffer strips for the same purpose. The grass or other vegetation type for this purpose should be summer-tolerant to be effective (Ranga et al., 2015b). Vegetation activity in badlands is also indicative of erosion processes. Vegetation has a stabilizing affect to soil erosion; in Chambal valley increase in vegetation after the monsoon may be indicative of reduction in soil erosion whereas on the onset of monsoon, due to least vegetation activity, soil erosion could be drastically high.
Socio-economic implications: The interactions between social and natural processes impacting upon land degradation are often complex and locale-specific (Blaikie, 1985). Land degradation has several socio-economic implications, including loss of agricultural land (Pani and Mohapatra, 2001a, 2001b), agricultural productivity (Biggelaar et al., 2003), worsening food security (Scherr and Yadav, 1996), lower levels of economic activity and low standards of living (Ezaza, 1988) and poor health status (Scherr, 1999). Land degradation has been affecting the livelihoods of many primary producers in Asia and Africa (Joshi et al., 1996; Scherr, 1999; Scherr and Yadav, 1996, 2001). Damage caused by gully erosion is found to be most severe in the alluvial plains of the semi-arid and arid zones in the developing world, where it threatens precarious subsistence-oriented agricultural systems. Gully reduces the size of agricultural land and also affects productivity through changes in hydrological conditions, soil structure and accessibility (Zglobicki and Baran, 2012; Pani and Carling, 2013).

Badlands constitute dynamic environments where they are formed, expand and disappear or are deleted following the changes in the equilibrium between natural processes and human activities (Torri et al., 2000). In arid and semi-arid regions where vegetation is very sparse and soils are rich in clay minerals, severe erosion induces the badlands, characterized by steep slopes with rills and gullies as their main features (Liberti et al., 2009). The badlands of the Chambal valley are now subjected to levelling for agriculture, but the levelling is not sustainable and requires continuous efforts (Ranga, 2013). Monitoring of badlands becomes an important aspect for policy making and environmental planning (Poesen et al. 2012).

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Day 2  
Agra to Sahso, Bindwakhurd and surroundings, and back  
Stay at Agra

Fig. 16. Google earth image of the area to be visited on Day 2.
The field trip to village Shaso and Bindwakhurd and its surroundings will be undertaken to see the severe ravine-affected terrain and the village landscape (Fig. 16). The much-discussed origin of ravine in peninsular India is of a geological origin and it has been suggested by many authors that this part has been rejuvenated in the recent geological past and the present topography has been carved out by accelerated stream action (Sharma, 1980). The entire stretch of river Chambal from Agra to Etawah, comprising of deep pools of water, can be seen as a glimpse of incised meander on the way to the study villages. Several deep, medium and shallow ravines exist together around the villages. Some classification is necessary to analyse the morphological characteristics of the ravine in this stretch. The depth of the ravines varies from 5 m to 60 m and more, with very narrow to wide base width (5-20 m) and steep side slopes. Most of the ravines appear here in “V” shape, which is developed where the soil and sub-soils are commonly friable and easily cut by flowing water. It can be observed that the active gullies are in linear shape, and most of the gullies are very narrow, deep, and associated with long gullies (sometimes more than 5 km) which are most of the cases very uncontrollable by nature. The vertical caving section of a ravine head is characteristic of a very active gully which is very much prone to engulf the unaffected adjoining land which is most of the cases agricultural land. The other pattern of the ravines is also very much present here like bulbous, compound and trellis pattern, which are quite interesting to study to understand the stages of growth of the ravine. Some part of the ravine also eroded and lowered down due to the natural process mainly by collapsing process. At the same location of Sahso and Bindwa Khurd villages, the local farmers’ dwell with the ravine land and its encroachment is very much noticeable.

Day 3
Agra to Emiliya Village and back to Agra
Depart from Agra

Fig. 17. Google earth image of the area to be visited on Day 3.
The day will be spent in visiting sites near Emiliya village in Uttar Pradesh, around a meander bank of the river Chambal (Fig. 17). The area is the confluence zone of the Yamuna River and the Chambal River, a very interesting study site. Distinct fluvial landforms, deeply incised drainage system, and morpho-tectonic features are very much observable in this region. It is also well known for badlands having a labyrinthine network of deeply incised gullies and ravines with a variable depth of 50 to 60 m at places along the rivers. The discharge capacity, degree of incision, and channel width and depth of Chambal River is significantly more than that of the Yamuna in this stretch. Hence, the Chambal constitutes the trunk stream of the region.

According to Geological Survey of India (GSI), “The river course downstream of the Chambal-Yamuna confluence, which is at present known as the Yamuna, entirely due to mythological and historical reasons, has the same channel geometry and gradient as that of the Chambal River upstream of the confluence. This suggests that the Yamuna, in reality, follows the course of the Chambal River below the confluence of the two rivers” (www.portal.gsi.gov.in/gsiDoc/pub/cs_morphotectonics.pdf). Thus the area gives an insight to the origin of ravines and role of morphotectonics in the formation of badlands.
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<td>14 November 2017</td>
<td>Darjeeling Town and surroundings Stop 1: Ghum Stop 2: Tiger Hills (04-30am) Stop 3: Old Monestary, Ghum, Batasia Loop Stop 4: Bannockburn Tea Garden landslide Stop 5: Happy Valley Tea Garden Stop 6: Tibetan Refugee Centre Stop 7: Himalayan Mountaineering Institute, Tenzing Rocks</td>
<td>Darjeeling</td>
</tr>
<tr>
<td>16 November 2017</td>
<td>Siliguri to Kalimpong Stop 1: Sevok in Tista Valley Stop 2: River Lish and Gish Stop 3: Kalijhora – TLDP Stage IV Stop 4: Rambhi – TLDP Stage III Stop 5: Tribeni confluence at Pesoke</td>
<td>Kalimpong</td>
</tr>
<tr>
<td>17 November 2017</td>
<td>Kalimpong to Bagdogra Airport Bagdogra Airport to Delhi by flight</td>
<td>New Delhi</td>
</tr>
</tbody>
</table>
A. DARJEELING HIMALAYAS: AN INTRODUCTION

Darjeeling Himalayas (Fig. 2) is located above 300 m contour line in the mountainous part of Darjeeling district and is bounded by latitudes 26º50’00”N to 27º13’05”N and longitudes 87º59’30” to 88º53’E. It has an area of 2417 sq. km, spread over three Hill Sub-divisions of Darjeeling Sadar, Kalimpong and Kurseong, where, according to the 2001 Census, approximately 808,293 people reside. Kalimpong has recently become a separate district. The region is highly prone to landslides, often causing disruptions to socio-economic activities as well as destruction of life and properties.

Darjeeling Himalayas has an elevation range of 2000-3000 m, and occurs as the foreland of the Kanchenjunga massif. During the period of summer monsoon, moisture-laden wind from the Bay of Bengal gets obstructed along this foreland, which often leads to heavy to very heavy rainfall. The incessant heavy rainfall causes rapid runoff, which, in the current scenario of extensive deforestation, urbanisation and other activities that encourages high soil loss, favours landslides, floods and mud flows. More often the damages after heavy rainfall events are enormous. The major aims of this field trip are to inspect some of the landslide-affected terrain features, the impact of the landslides on the surrounding landscape, and the land uses that trigger the landslides in the region. Since Darjeeling area is famous for tea growing, some of the tea gardens will also be visited.
Climate

Darjeeling Himalayas is situated in the humid tropical belt with a monsoonal circulation. At Darjeeling town, the temperature fluctuates between -5\(^\circ\)C and 27\(^\circ\)C, while in the plains at the foothills of the Himalayas the temperature varies 4\(^\circ\)C and 42\(^\circ\)C in the plains. The annual precipitation varies from 2000 to 4500 mm, and in an exceptional year it may reach 6000 mm. The rainy season starts by the end of May and continues up to the beginning of October. The mean maximum daily rainfall at Darjeeling is 172 mm but it may reach up to 500 to 600 mm. Of special importance are the continuous rains or heavy rains for 3-4 consecutive days. The mean monthly rainfall and temperature for Darjeeling district as a whole (averaged from several station data), and for the hills and the plains, are given in Table 1.

Table 1. Mean rainfall and temperature in the hills and the plains of Darjeeling district

<table>
<thead>
<tr>
<th>Month</th>
<th>Hills</th>
<th></th>
<th></th>
<th>Plains</th>
<th></th>
<th></th>
<th>Darjeeling district</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rainfall (mm)</td>
<td>Temp. ((^\circ)C)</td>
<td>Rainfall (mm)</td>
<td>Temp. ((^\circ)C)</td>
<td>Rainfall (mm)</td>
<td>Temp. ((^\circ)C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jan</td>
<td>14.05</td>
<td>10.53</td>
<td>19.85</td>
<td>17.26</td>
<td>16.95</td>
<td>13.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>19.96</td>
<td>12.09</td>
<td>21.19</td>
<td>19.6</td>
<td>20.58</td>
<td>15.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>48.96</td>
<td>15.56</td>
<td>52.88</td>
<td>23.45</td>
<td>50.92</td>
<td>19.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>108.96</td>
<td>18.62</td>
<td>129.56</td>
<td>26.27</td>
<td>119.27</td>
<td>22.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>314.32</td>
<td>19.5</td>
<td>228.8</td>
<td>27.6</td>
<td>271.56</td>
<td>23.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>662.46</td>
<td>20.72</td>
<td>598.43</td>
<td>29.19</td>
<td>630.45</td>
<td>24.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>845.49</td>
<td>21.71</td>
<td>820.32</td>
<td>28.12</td>
<td>832.91</td>
<td>24.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>644.81</td>
<td>21.88</td>
<td>621.15</td>
<td>28.81</td>
<td>632.98</td>
<td>25.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>549.84</td>
<td>19.94</td>
<td>47.35</td>
<td>27.35</td>
<td>510.1</td>
<td>23.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>142.23</td>
<td>18.36</td>
<td>146.32</td>
<td>26.65</td>
<td>144.28</td>
<td>22.51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>24.92</td>
<td>15.23</td>
<td>35.55</td>
<td>23.02</td>
<td>30.24</td>
<td>19.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>6.39</td>
<td>11.92</td>
<td>14.4</td>
<td>19.11</td>
<td>10.4</td>
<td>15.52</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The aerial distribution pattern of rainfall in the region does not show any direct correlation with the elevation. The major factors for the aerial pattern are the exposure towards the humid air masses and the distance from mountain front. The higher rainfall of 3500-4500 mm is recorded at the southern edge of the mountain, but it abruptly declines to 2000-2500 mm northward due to wind shadow. Further north the rainfall increases again to 3000 mm on the elevated hill slopes and then declines below 2000 mm in the valley of the Rangit River (Starkel et. al, 2000).
Relief
Darjeeling Himalaya rises abruptly from the North Bengal plain, the elevation changing rapidly from 100-130 m above sea level (a.s.l) to 2000-3000 m a.s.l within a distance of few kilometres. Once in the hilly terrain, narrow ridges separated by closely-spaced V-shaped valleys become numerous. Convex and straight slopes prevail, where the slope varies between 15° and 40°. It is also not uncommon to find some steep walls with undercutting and rock falls. The zone of Siwalik foothills, which is common in the western Himalayas, is practically absent here. The scarp-dissected front of the mountain reaches an elevation of 1500-1800 m over a distance of 10 km.

Streams, river valleys and channel characteristics
The narrow channels of the headwater streams dissecting the rocky terrain have a slope of 20-60%, which decline to 5% and less downstream in the foothills, where widening of the valley floor takes place. This foothills zone is called the “Terai”, where the wider valley floors are frequently filled up with large boulders transported by debris flow. The main river, the Tista, carries water from the Kanchenjunga Massif and the Sikkim Himalaya through its deep and narrow meandering valley that has been cut in the bedrock. Coming out of the mountains the Tista has formed a vast alluvial fan with many palaeo-channels that were formed by large floods and avulsion. A number of smaller rivers, i.e., the Balason, the Mahananda, the Lish and the Gish, originate in the Darjeeling Himalaya, and have formed braided courses on the plains, which are overloaded with sediments. These streams form smaller fans, the apex part of which could be noticed at the entrance of the mountains. Fragments of higher fan levels with well-develop soil profile are preserved between the alluvial fans. The shape of the terraces and the fan systems on the Terai piedmont zone is irregular, and are partly controlled by tectonics (Nakata, 1972).

The relief of the valley floors and river channels within the mountains exhibits features of youthful stage of evolution, which are characterized by steep ungraded channels, narrow floors, steep and undercut valley sides and hanging tributary valleys. The valley reaches of the Tista and the Great Rangit Rivers in the Darjeeling Hills are characterized by 100-200 m wide valley floors, having straight or sinuous channels with point bars, rare benches of terraces and steep alluvial fans. The valley itself, with a gradient of 2 0/00, has a character of incised sinuous or meandering canyon with vertical undercutting on one or both river banks. The tributary valleys along the Tista canyon have higher gradients of 2-150/00, which become still steeper in the headwaters area, i.e., 20-30 0/00.
A slightly different longitudinal profile of streams can be noticed in the valleys directly dissecting the mountain edge, i.e., the valleys of the Balason, the Mahananda, the Lish and the Gish. Although gradients at the headwaters are steep and are controlled by lithology and mass movement, as in the Tista catchment, the valley floors downstream become broader. Aggradation prevails despite a higher gradient. Finally, the channels in the Terai zone mingle over the alluvial fans and are either dissected in their apex pat (as in the case of the Balason), or continuously aggrade (like in the case of the Lish and the Gish). The Tista and the Mahananda are characterised by frequent avulsions during the last two centuries.

**Landscape evolution**

The young relief features of the Darjeeling Hills reflect intensive Quaternary uplift and the consequent vigorous valley down-cutting. The present-day uplift in the marginal part may still reach 3-4 mm per year. However, a number of accordant flat surfaces in the hills signify periods of stability in between the periods of different uplifts. Two such level surfaces, named the Gorubathan Surface and the Rangamati Surface, preserve the fragments of elevated fans with boulders, and suggest that during the periods of relative tectonic stability, stream aggradation spread upstream into the hills.

Many valley floors exhibit narrow terrace benches. One of these could be noticed upstream of the Kalijhora Creek along the Tista valley, where the bench thickness is about 40 m. It is formed of loamy sand and fine gravel, indicating that aggradation and delivery of suspended load took place during high floods.

**Role of extreme climatic events in landscape evolution**

It has been observed that under a dense forest cover the steep mountain slopes are usually stable, in the sense that some equilibrium is maintained between erosion and deposition on them, even during heavy rainfall events. But after deforestation takes place, both the slopes and the river channels frequently pass the threshold of erosion during extreme rainfall events. Shallow slides or slumps have been observed to have formed on the steeper slope segments when the daily rainfall exceeded 150 mm, or after continuous rainfall for about 3 days, totalling 200-300 mm. Such events generally occur once in 2 years.

Darjeeling Himalayas mainly experiences local downpour, but during extreme events like the one in October, 1968, when 600-1100 mm was recorded in 54 hours, there follows an extensive and simultaneous formation of debris flows along the whole length of the slopes and along the gullies. Such events have a recurrence interval of about 30-50 years. Normal flood events generally cause minor changes along the slopes, restricted mainly to incision due to washing of the finer sediments. Under
extreme events considerably higher channel aggradation and avulsion take place, which coincide with the transformation of slopes. This simultaneous change in the slope and the channel profile is linked to the direct contact of the slopes and the channels in narrow valleys with the occurrence of rare continuous rains. Deforestation accentuates the process, as was evident from the location of mass-movement sites during October, 1968, when the cultivated fields, devoid of forest cover, were observed to be 10-20 times more numerous than on the forested lands. Under such scenarios the overloaded streams perform more lateral erosion and aggradation than down-cutting. The major exception to this behaviour in the region is River Tista, which does not show any change towards aggradation in its uplifting marginal zone.

Geology and Soils
Darjeeling Himalaya is separated from the foredeep of the Ganga-Brahmaputra plain by two active tectonic lines in the zone of subduction of the Indian block (Fig. 3), which created a sequence of over-thrusts pushed southwards, and deepening to the north (Fig. 3). The rock formations from north to south consist of the moderately resistant Darjeeling Gneisses, the Daling Metamorphics of varying resistance (i.e., phyllite to quartzite), and the Damuda Shales with coal beds. The Main Boundary Fault separates the Damuda Shales from the narrow thrust of the Siwalik, built of Tertiary sandy molass deposits. The Siwalik formations are separated from the subsiding Bengal Plain by the active Himalaya Front Tectonic Line (Table 2; Fig. 3). Some fresh tectonic scarps and exposures of Tertiary over-thrust on the alluvium suggest that the movement is continuing. The uplift in the Eastern Himalayas is calculated to be of the order of 0.5 to 2.0 mm/year.

Fig. 3.
Geological map of Darjeeling district.
Table 2. Litho-succession of the Darjeeling Himalayas

<table>
<thead>
<tr>
<th>Sub-recent and Recent alluvium (Pleistocene to recent)</th>
<th>High-level terrace deposits of gravel, boulder, nd sand, constituting the Terai</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unconformity</strong></td>
<td><strong>Pebbly sandstone and conglomerate</strong></td>
</tr>
<tr>
<td>Structural Unit I</td>
<td><strong>Upper</strong> (400-500 m+)</td>
</tr>
<tr>
<td>Siwalik Group (Mio-Pliocene)</td>
<td>Middle (800-1250 m)</td>
</tr>
<tr>
<td></td>
<td>Medium grained micaceous dstone</td>
</tr>
<tr>
<td></td>
<td>Lower (200-250 m.+</td>
</tr>
<tr>
<td></td>
<td>Clay stone, siltstone and fine grained sandstone</td>
</tr>
<tr>
<td><strong>Main Boundary Fault</strong></td>
<td></td>
</tr>
<tr>
<td>Acid intrusive</td>
<td>Quartz vein</td>
</tr>
<tr>
<td>Lamprophyre</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Unconformity</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Dalingkote Formation (450-600 m +)</strong></td>
</tr>
<tr>
<td>Structural unit II</td>
<td><strong>Hard quartzitic gritty sandstone (medium-coarse grained) shale, slate, carbonaceous sandstone with crushed coal seams.</strong></td>
</tr>
<tr>
<td>Damuda Group (Permian)</td>
<td><strong>Chunabhati Formation (450-600 m.)</strong></td>
</tr>
<tr>
<td></td>
<td>Fine medium grained micaceous quartzitic sandstone.</td>
</tr>
<tr>
<td></td>
<td><strong>Rongtong Formation (350 m. +)</strong></td>
</tr>
<tr>
<td></td>
<td>Quartzitic sandstone of variable grain size siltstone slaty shale.</td>
</tr>
<tr>
<td><strong>Daling Thrust (Overthrust)</strong></td>
<td></td>
</tr>
<tr>
<td>Structural unit III</td>
<td><strong>Daling Formation (pre-Permian, but age unknown)</strong></td>
</tr>
<tr>
<td></td>
<td>Phyllitic schist and quartzite.</td>
</tr>
<tr>
<td><strong>Thrust</strong> (zone of sheared and lineated felspathic biotite-schist and gneiss)</td>
<td></td>
</tr>
<tr>
<td>Structural unit IV</td>
<td><strong>Darjeeling Gneiss</strong></td>
</tr>
<tr>
<td></td>
<td>Coarsely micaceous migmatitic gneiss and schist with eyed lenses of calc-silicates.</td>
</tr>
</tbody>
</table>

**Source:** Records of the Geological Survey of India.
The mountain slopes are covered with sandy to silty soils, usually 0.5 to 2.0 m thick (up to 4 m on the flat surfaces). They change from red clay soils in the lowest elevation to grey brown forest soils in the higher elevations. Soils are generally permeable but their thickness and physical parameters vary from place to place, depending on the slope gradient, lithology, weathering potentials of the bedrocks and land use.

Landslides
Due to the above tectono-geomorphic setting of the hills and destabilization of the hill slopes by increasing anthropogenic activities, the Darjeeling-Kurseong tract has emerged as one of the foremost landslide-prone areas in India (Basu and Starkel, 2000). Landslides and other types of slope failures, triggered by heavy monsoon rains, now occur almost every year. Ghosh et al. (2012) have identified three main types of slope failure in the area: shallow translational rockslides, shallow translational debris slides, and deep-seated rockslides. The shallow translational rockslides are most common in the area. The Ambootia Landslide of October 1968 is considered to be the largest landslide in modern time, and involved a deep-seated rockslide that continued to remain active for the next 1-2 decades (Starkel, 2010).

Hydrology
The distribution of rain water is regulated rather by the soil permeability than the slope gradient. The assessment of the infiltration rate in some localities showed very high values reaching even up to 70mm/min, but at or near landslide niches they may go down to 2-5 mm/min. However, the high soil permeability prefers/induces subsurface runoff and high seepage pressure. The overland flow is thus very low i.e., after a rainfall of 50mm with an intensity of 0.5mm/min, the overland flow measured only 1-6 litter/min Froehlich et. al, 1989).

An attempt was made by Sarkar (1998) to assess infiltration rates at different sites in Darjeeling town which revealed rapid infiltration during the first 15 minutes, followed by a sluggish infiltration over the nest hour. Forest-covered slopes recorded more infiltration than the non-forested areas, i.e., 39 mm/minute at Katapahar area and only 6.3 mm/minute at an urbanised area near Sailabas (Fig. 4). It was observed that during the heavy monsoon rains most roads acted as the surfaces of high runoff/overland flow. One study on a slope of 17º near St. Paul’s School showed that the peak runoff reached a high of 80% of the total rainfall (Fig 5).

In the river channel, the hydrograph shows frequent peaks during the rainy season. In the Tista River the mean annual fluctuation exceeds 5 m, but during extreme events it reaches 20 m (e.g., during the extreme flood of 1968). The fluctuation of discharge
depends on the size of the basin and on the duration and extension of heavy rains. In
the case of the Mahananda River, the discharge fluctuated during 1985-87 between
0.7 to 758 cumec (Sarkar, 1989). The runoff coefficient reached 60-80% and the
calculated specific runoff during extreme events exceeded at least by 10-20 m3/km2
in the 2nd and the 3rd order stream catchments (Froehlich and Starkel, 1987).

Vegetation
There are three distinguished vertical zones of evergreen forest in Darjeeling
Himalayas (Schweinfurth, 1968). The tropical forest belt reaches the elevation of
900-1000 m a.s.l., characterised by the Sal forest (Shorea robusta). The sub-tropical
belt between 900-1800 m a.s.l. supports mixed vegetation with Castanopsis,
Machilus, Schina, etc. The upper forest belt up to the peak of the mountains is
represented by temperate species such as Quereus, Acer, Batula, Alnus,
Rhododendron, and the exotic Cryptomeria japonica.
Socio-economic Aspect

Darjeeling district comprises of four sub-divisions, namely Sadar sub-division, Kalimpong sub-division, Kurseong sub-division and Siliguri sub-division. The Darjeeling hills area is spread over the first three sub-divisions. Siliguri sub-division is in the plains. Kalimpong has recently become a separate district.

Population growth and Natural resources

British East India Company took over Darjeeling from the King of Sikkim in 1835 when only 100 souls of Lepcha community were the inhabitants. With the construction of the Pankhabari Road in 1840 and of the Hill Cart Road in 1869, and following the development of tea plantation, the population of Darjeeling started to increase rapidly in every decade.

The first official census of the district was carried out in the year 1871-72 when the total population was found to be 94712, with an average population density of 81 persons per sq mile. However, this census was subsequently found out to be defective, and the results appeared wrong.

The regular influx of immigrants from Nepal, and gradual residence of people from different parts of India since 1980s helped to create a multi-lingual and multi-cultural society in the area. Very high population growth was observed in the urban areas and road-side village market areas. The Census data on population in different hill sub-divisions of Darjeeling district for 1981 to 2011 reveal a steady growth of population during the last four decades. Kurseong and Kalimpong sub-divisions are registering higher growth percentage (Table 3).

Table 3. Total population in the three hill subdivisions of Darjeeling district (1981-2011)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sadar</td>
<td>281346</td>
<td>347912</td>
<td>388107</td>
<td>310576</td>
<td>10.4</td>
</tr>
<tr>
<td>Kurseong</td>
<td>111302</td>
<td>146640</td>
<td>177264</td>
<td>140721</td>
<td>26.4</td>
</tr>
<tr>
<td>Kalimpong</td>
<td>158726</td>
<td>190266</td>
<td>225220</td>
<td>202239</td>
<td>27.4</td>
</tr>
<tr>
<td>Total</td>
<td>551374</td>
<td>684818</td>
<td>790591</td>
<td>653536</td>
<td>18.5</td>
</tr>
</tbody>
</table>
The steady growth of population in Darjeeling hills area since 1872 is mainly due to two reasons: first, the development of tea industry, and second, the influx of settlers. The job opportunities provided by the Tea Estates attracted huge work force to their tea gardens from the plains, and many more came in as job-aspirants. According to the 1911 census, the Tea Estate workers accounted for more than two-third of the total population of the district. When the tea industry passed through a serious crisis during the end of Nineteenth Century, prices fell greatly between 1896 and 1901 and many Tea Estates were no longer able to work at a profit. A few gardens closed and few others had to reduce their work force. Despite the fact that Darjeeling’s tea industry was revived somewhat after the independence, and its fame for quality products maintained, the age-old plantations, worn-out and obsolete machineries and stiff competition from new gardens in other parts of the country and elsewhere became worrisome. Trade and commerce, especially related to tourism, started to flourish in and around Darjeeling town and Kalimpong. The major work force, however, remained with the Tea Estates. Surprisingly, a look at the Census data from 1981 onwards reveals that the workers always constituted less than 40% of the total population (Table 4).

**Table 4. Percentage of workers in population of Darjeeling district (1981-2011)**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sadar</td>
<td>35.7</td>
<td>32.0</td>
<td>34.4</td>
<td>38.0</td>
</tr>
<tr>
<td>Kurseong</td>
<td>34.6</td>
<td>31.19</td>
<td>35.7</td>
<td>36.6</td>
</tr>
<tr>
<td>Kalimpong</td>
<td>37.4</td>
<td>35.9</td>
<td>358.8</td>
<td>39.0</td>
</tr>
<tr>
<td>Total</td>
<td>36.0</td>
<td>33.1</td>
<td>36.0</td>
<td>38.0</td>
</tr>
</tbody>
</table>

**Land use**

The dominantly forest landscape of Darjeeling hills started to change when commercial tea plantation began in the mid-19th century. The British started to build roads and establish the first tea garden in 1850-60, which activities necessitated forest clearance. By the end of the 19th century more than 200 tea gardens were developed, spread over 200 sq. km area. The major concentrations took place along the two main roads and reached up to an elevation of 1800-2000 m a.s.l. The area under forest diminished steadily from 51.5% of the total area in 1901 to 38.27% in 2014 due to the ever-increasing population pressure, and also due to the slash and burn system of cultivation. This is despite the fact that a Darjeeling Forest Division was established in 1878 to restrict deforestation and to start new forest plantation.
Presently the district has its 22.5% of land under tea plantation and 37% under other cultivations (Fig. 6). The main crop is tea, but during the past 50 years tea economy is under increasing threat, leading to abandonment of many tea gardens. Also, most tea bushes are older than 80 years, and so have declining productivity and quality. Other cultivated areas are expanding rapidly due to population pressure. Maize, potato, millet, paddy, orange, cardamom, ginger and vegetables are grown on the narrow slope terraces. Due to shortage of land, even the steeper slopes are put under cultivation.

As tourism is becoming more popular, the towns are getting more crowded, creating problems of space for house construction, as well as for water and other amenities. In the towns many houses are being constructed on steep slopes with weathered rocks, making them unstable. Construction of many new roads is destabilizing the slopes. As a result, the susceptibility of the land to landslides is increasing manifold during heavy rains. As deforestation progressed, the drainage system got impacted, and it led to the paucity of water for the urban localities. The natural resources of Darjeeling Himalayas need immediate conservation measures and a viable land use plan for sustainable resource use.

**Places of Tourist interest**
There are many places which attract the tourists in huge number. The places are as follows:
Tiger Hill, Batasia Loop, Chowrastha and Mall, Peace Pagoda, Roch Garden and Ganga Mayeea Park, Botanical Garden, Padmaja Naidu Himalayan Zoological Park, Himalayan Mountaineering Institute, Dali Monastery and Ghum Monastery.
B.DESCRIPTION OF THE FIELD SITES

Day 1: 12/11/2017
New Delhi to Bagdogra Airport by Flight
Travel to Siliguri
Stay at Siliguri.

The first day will be spent in discussing the travel routes, the general characteristics of the area, and the logistics. During the period of visit two separate trips will be made from the base, Siliguri, to the mountains. The first trip will be made to Darjeeling. Returning back from there a trip will be made from Siliguri to Kalimpong.

Day 2: 13/11/2017
Siliguri to Darjeeling via Mirik
Stay at Darjeeling

The route from Siliguri to Darjeeling passes first through a flat-lying “Terai” terrain with lush green crop fields and tea gardens, with occasional rivulets, and then climbs gradually up the hills through a narrow road flanked by forest plantation, or tea gardens. Landslide scars can be seen at places. At least three halts will be made to appreciate the geomorphic features along the road.

Stop 1: The Balason – Rohini Alluvial Fan (on way to Dudhia and Mirik)
The rivers coming down from the Himalayas to the wide, open plains of North Bengal have developed a number of alluvial fans. Between the 300 m contour in the north and the 75 m contour in the south, these alluvial fans coalesce to form a piedmont zone. The fans between the Balason and the Rohini rivers cover an area of about 40 sq. km, and can be considered as the best-developed on way to Darjeeling. The two streams are the tributaries of the Tista River, and have catchments in the Himalayas. The variability of slope and sediment texture along these fans roughly determines the broad land uses on the fans. Land use is dominated by the tea gardens (45%), followed by forest (39%) and arable land (10%). The evolution and morphology of the fans are briefly described below.
Fan evolution
The fact that some thick boulder beds unconformably overlie the northward-dipping Siwalik strata (Pliocene-Pleistocene) at the base of the Eastern Himalayas suggests that the boulder formations originated sometime during the Pleistocene period, especially following a phase of uplift, tilting and partial denudation of the Siwaliks. This was also the period when the higher parts of the Darjeeling Himalayas were experiencing widespread glaciation. Periglacial conditions prevailed in the Manebhanjan-Sukhiapokhri-Ghum range (N26°57’ to N27°00’; E88°00’ to E85°20’). The main stream, the Balason River, and its major tributaries, the Rakti and the Rohini, brought down a large volume of periglacial debris and solifluction materials, which eventually got deposited as coalescing alluvial fans when the streams reached the foothills (Kar, 1962, 1969; Godwin-Austin, 1968).

Fan materials and modes of deposition
The fan materials are coarse-grained and poorly-sorted, and have developed immature sediment profiles (Basu and Sarkar, 1990). Usually gravels, cobbles and boulders predominate, while the quantities of sand, silt and clay are much less. The coarsest and thickest deposits occur near the fan heads. The maximum grain size and sediment thickness decrease rapidly towards the base of the alluvial fans. The roundness of coarse grains increases with increasing distance from the apex of the fans. Intermittent flush floods and mass movements are the notable modes of deposition here. Bank erosion and avulsion are also quite common.

Fan segments
Three broad zones can be identified on the fans. These are depicted in Fig. 7 and Fig. 8. Table 5 provides some important characteristics of these fans.

Table 5. Characteristics of alluvial fan segments

<table>
<thead>
<tr>
<th>Segment</th>
<th>Area (sq. km)</th>
<th>Area (% of total)</th>
<th>Slope (degree)</th>
<th>Materials</th>
<th>Major processes</th>
<th>Major land uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>10.23</td>
<td>25.70</td>
<td>3.5-10.0</td>
<td>Coarse-grained gravels, cobbles and boulders</td>
<td>Flash floods, debris-flow, solifluction and steam action</td>
<td>Forest, tea garden</td>
</tr>
<tr>
<td>Middle</td>
<td>18.26</td>
<td>45.87</td>
<td>1.5-3.5</td>
<td>Medium grained sand-silt with occasional boulders</td>
<td>Stream action and stream floods</td>
<td>Forest, tea garden, arable land</td>
</tr>
<tr>
<td>Lower</td>
<td>11.32</td>
<td>28.30</td>
<td>1.0-1.5</td>
<td>Fine grained sand, silt and clay</td>
<td>Stream action and stream floods</td>
<td>Forest, tea garden, arable land</td>
</tr>
</tbody>
</table>
Fig. 7.
Geomorphological map of the alluvial fans between the rivers Rohini Khola and Balason. Key to legend: 1. scarp, 15-25m; 2. scarp, 5-10 m; 3. limits of the Darjeeling Hills; 4. lower limit of the upper fan; 5. lower limit of the middle fan; 6. slope wash and mass movement materials; 7. landform due to mixed processes, including slope wash, mass movement and alluvial deposits; 8. boulder beds; 9. middle fan; 10. elevated tracts due to resistant rocks; 11. floodplain of Balason River; 12. river; 13. lower fan.
Fig. 8. Cross-profiles, showing stratigraphy and land use on the alluvial fans (source: Basu, S.R. and Sarkar, S. 1990).
Stop 2: Mirik
Mirik is a picturesque tourist spot nestled in the serene hills of Darjeeling district, and is the headquarters of Mirik subdivision. The name Mirik comes from the Lepcha words Mir-Yok, meaning "a place burnt by fire". Mirik has become a popular tourist destination for its climate, natural beauty and easy accessibility.

The centre of attraction at Mirik is Sumendu Lake, surrounded by a garden named Savitri Pushpaudyan (after Savitri Thapa, a martyr soldier of the Indian National Army, INA) on one side and rows of pine trees on the other. An arching footbridge, called Indreni Pool (named after Indreni Thapa, a martyr soldier of INA), links the two sides. A 3.5-km-long road encircles the lake and is used for a walk and to view the Kangchenjunga Peak on the far horizon. It is believed that the lake is of tectonic origin, but so far there is no work to substantiate the view.

Another geomorphic attraction in the area is a domal topography. Although it looks like a dissected intermontane plateau, the sediments in the core part indicate that the landscape originated due to glacial deposition (Fig. 9). Most parts of the landscape are now deforested to make way for tea cultivation. It has encouraged the formation of chutes that have aggravated the landslide events.

Fig. 9.
Deforested Mirik domes, a major cause for landslides in the area
Stop 3: Simana Basti
Simana Basti is a village in Suknapokhri Tehsil of Darjeeling district, and is located 79 km away from sub-district headquarters Sukhiapokhri and 69 km away from Mirik on way to Darjeeling. The village is very close to Nepal border. The route to this border village provides a breath-taking view of the Himalayan landscape.

Day 3: 14/11/2017
Darjeeling town and surroundings
Stay at Darjeeling.
Darjeeling town, with a population of more than 200,000, is a major tourist destination in India, especially as a summer resort. The town was connected with the plains by railways way back in 1881. In June 1950, following a catastrophic rainfall of more than 1000 mm, the town was severely affected by numerous landslides. Although Darjeeling has not experienced such a calamity after that event, the population explosion in the town is creating numerous problems for its inhabitants. Among these, water for drinking and other household purposes is becoming a highly scarce resource. Construction of houses has increased manifold, so much so that urbanization is now spreading downhill, as there is no room in the upper part of the town. Desperate efforts to stay within the town limits are forcing people to build multi-storied houses on unstable steeper slopes with highly weathered rocks, which are endangering the life and property of the inhabitants. The day will be spent on visiting some of the important places in and around the town.

Stop 1: Ghum
Ghum, situated at a height of 2250 m above mean sea level, and located only 6 km away from Darjeeling on the Siliguri-Darjeeling highway, is a small market town, as also a major watershed divide between some of the important stream catchments in the region. The E-W orientation of the ridge section here is a reason for its high cloudiness, higher humidity and long-duration precipitation. The crest zone is overgrown with Cryptomeria japonica forest.

Ghum is famous for having one of the highest railway stations in the world for the more than a century-old railway line from Siliguri to Darjeeling, called the “Darjeeling Himalayan Railways” (also called the “Toy Train”). This small-gauge line was earlier the only means of bulk transportation of men and materials from the hill to the plains and vice-versa in slow-moving carriages, but as road transport facilities improved in the post-independence era, it lost much of its relevance. Yet, it continued to have a huge tourist attraction, and therefore, the Indian Railways tried to maintain the track and the carriages despite the technology becoming obsolete and difficult to maintain. Till very recently this railway line was a UNESCO World Heritage Site.
Construction of the Darjeeling Himalayan Railway started in 1879 and the railway track reached Ghum on 4 April, 1881. Until 1878, the journey from Calcutta (now Kolkata) to Darjeeling used to take 5-6 days, using steam-engine-pulled trains, crossing the Ganga River by steam ferry at Sahebganj, and then using bullock carts or palanquins for destinations further north. In 1878, Siliguri was put on the railway map of India, cutting down the journey from Kolkata to two days. By 2007, the train travel time from Kolkata to New Jalpaiguri (a new railway station 6 km from Siliguri) was reduced to about 10 hours. The travel time by road from Siliguri to Darjeeling via Ghum now takes about 3–4 hours. By contrast, a journey by the Darjeeling Himalayan Railway takes about 6–7 hours to cover the same distance. Consequently the slow train has lost its advantage. However, tourists, both domestic and international, have always been found to seek a ride on this vintage train, especially because of the kaleidoscopic views of the Himalayan terrain and the local socio-cultural pattern they get from a slow-moving train. Therefore, the Indian Railways have decided to continue the train service, despite the problems of maintenance, viability, etc.

Ghum is also the meeting point of several roads. The road from Siliguri to Darjeeling, best known as the “Hill Cart Road” runs through the town. A road from here goes via Sonada to Kurseong, which is at a distance of 24 km. Kalimpong is about 45 km away from Ghum, and is reached via Lopchu. Another road goes to Mongpu and from there to the Kalimpong-Siliguri road. Sukhiapokhri, almost on the India-Nepal border, is 11 km away, on the road to Mirik.

Stop 2: Tiger Hill
Tiger Hill, at a height of 2590 m above mean sea level, is the summit part of Ghum, and is an important tourist destination, especially because it provides a panoramic view of the Mt. Evareast and the Mt. Kangchenjunga together on sunny days. At sunrise, as the slanting sun rays gradually brighten up the snowy peaks of Mt. Kangchenjunga in multitude of colours, while the lower parts still remain under dark shades, the observers get a unforgettable view of the majestic mountain, and a celestial experience (Fig. 10). Mount Everest (8848 m), occurring further away, is faintly visible, especially on cloud-free sunny days. Mt. Makalu (8481 m), although at a lower height than Mt. Everest, looks higher due to the curvature of the Earth, as it is several kilometres closer than Mt. Everest. The distance in a straight line from Tiger Hill to Mt. Everest is 172 km.

On a clear day, Kurseong town is also visible at a distance in the south, as also the Tista River, Mahananda River, Balason River and Mechi River, all meandering down to the plains in the south. The Chumal Rhi mountain of Tibet, about 135 km away, is also visible over the Chola Range. Close to Tiger Hill is the Senchal Wildlife Sanctuary.
Stop 3: Old Monastery at Ghum
The actual name of the old Ghum Monastery is “Yiga Choeling”. The monastery belongs to the Gelukpa or the Yellow Hat sect of Buddhism, and is known for its 15 feet (4.6 m)-high statue of the Maitreya Buddha. The external structure of the building was constructed in 1850 by a Mongolian astrologer and monk, Sokpo Sherab Gyatso, who was head of the monastery until 1905. In 1909, Kyabje Domo Geshe Rinpoche Ngawang Kalsang, popularly known as Lama Domo Geshe Rinpoche, succeeded Sherab Gyatso as head. It was he who commissioned the statue of the Maitreya Buddha, and he remained head until 1952. During the Chinese occupation of Tibet in 1959 many high ranking abbots fled to India and took refuge in the Yiga Choeling monastery. In 1961, Dhardho Rinpoche became head of the Yiga Choeling monastery. Three years after his death in 1990, a boy named Tenzin Legshad Wangdi was recognised as his reincarnation. On 25 April 1996 he was enthroned at the Kalimpong Tibetan ITBCI school. The thirteenth in the line of Tulkus, Tenzin Legshad Wangdi, still goes by the name of Dhardo Tulkus. He is studying Tibetan Philosophy at Drepung Loseling University in South India.

Under the supervision of Dhardho Rinpoche, a Managing Committee was set up in order to improve the monastery’s functioning. Presently the monastery is meeting its needs through donations and contributions from local devotees.
Stop 4: Bannockburn Tea Garden & Landslide

The Tea Estate at Bannockburn (N27º 03’, E88º 17’) is one of the oldest tea gardens in Darjeeling area (Fig. 11). It is situated along the eastern valley side slope of the Rangnu Creek. The long, step-like slope of 10º-15º is dissected by tributary valleys that are up to 200 m deep. The slope is also characterised by several small depression-like features that actually are the scar marks left by landslides and shallow mudflows. The thickness of loose deposits varies from 4 to 10 m on gentler sloes, but bare rocky surfaces also exist. At least 60% of the area is occupied by terraced tea plantation, which accounts for more than 500 ha. Village settlements and small gardens occur on the steeper slopes. Discontinuous areas of untended forests (jungle) used to occupy an area of at least 20% of the whole garden area in 1968, but now the jungle area has shrunk considerably, and only a few remain with weeds and bushes yielding poor-quality fodder.

Froehlich and Starkel, (1987) & Froehlich, et al, (1989) carried out a detailed measurement of rainfall, infiltration rate and run-off on a spur in the Bannockburn Tea Estate. They concluded that the reasons for the formation of hundreds of shallow landslips, mudflows and debris flows in the Tea Garden after a high rainfall event in October 1968, was high permeability of the substratum. The rainfall event caused a very high seepage pressure, which led to the slips and damages in 20-25% of the garden’s area. They also estimated that individual rainfall events, causing downpours exceeding 200-300 mm, might result in recurrence of such slips on the steep slopes, as was noticed during 1983 and 1987. Based on the above study it may be concluded that the major land slips that occurred in this Tea Estate in 1950, 1968, 1980, 1983, 1987, 1990 and 1998, were all due to some high individual rainfall events, each exceeding 200 mm. Fig. 11 shows the location of some of the old and new landslides, while Table 6 enumerates the landslide area in each sector of the Estate.

Table 6. Tea and landslide areas in Bannockburn Tea Garden (Source: Bannockburn Tea Estate)

<table>
<thead>
<tr>
<th>Sector No.</th>
<th>Total Tea area (Acres)</th>
<th>Total Landslide area (Acres)</th>
<th>Sector No.</th>
<th>Total Tea area(Acres)</th>
<th>Total Landslide area (Acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>39.23</td>
<td>–</td>
<td>8.</td>
<td>32.81</td>
<td>3.68</td>
</tr>
<tr>
<td>2.</td>
<td>44.30</td>
<td>0.40</td>
<td>9.</td>
<td>21.63</td>
<td>3.40</td>
</tr>
<tr>
<td>3.</td>
<td>25.58</td>
<td>1.54</td>
<td>10.</td>
<td>35.17</td>
<td>2.51</td>
</tr>
<tr>
<td>4.</td>
<td>32.63</td>
<td>0.85</td>
<td>11.</td>
<td>30.41</td>
<td>5.30</td>
</tr>
<tr>
<td>5.</td>
<td>9.75</td>
<td>0.33</td>
<td>12.</td>
<td>35.48</td>
<td>4.84</td>
</tr>
<tr>
<td>6.</td>
<td>26.55</td>
<td>1.85</td>
<td>13.</td>
<td>27.12</td>
<td>4.74</td>
</tr>
<tr>
<td>7.</td>
<td>12.88</td>
<td>0.80</td>
<td>14.</td>
<td>15.67</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>389.21</td>
<td>30.24</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 11. Landuse and landslide in Bannockburn Tea Estate.
Stop 5: Happy Valley Tea Estate
The Happy Valley Tea Estate, located 3 km to the north of Darjeeling town, was established in 1854, and is Darjeeling’s second oldest tea estate (after the Steinthal Tea Estate that was established in 1852). Spread over 177 ha area (440 acres), it is situated at an elevation of 2100 m above mean sea level, and employs more than 1500 workers. This is also one of the highest tea factories in the world.

David Wilson, an Englishman, had originally named the garden Wilson Tea Estate and had started tea cultivation by 1860. In 1903, the Estate was taken over by an Indian, Tarapada Banerjee, who was an aristocrat from Hooghly (near Kolkata). By 1929, Banerjee also bought the Windsor Tea Estate nearby, and merged the two estates under the name of Happy Valley Tea Estate. Although the Estate worked fine for decades, and exported some of the finest quality tea to the world markets, the slump in tea industry at the beginning of this Century and old technologies being pursued for more than a century led to a major crisis, forcing closure of the Estate. In 2007 the Estate was bought by the owners of the Ambotia Tea Group, which established a new factory within the premises, and started modernization process, replanting and switching to organic farming. Finally, the estate reopened to public in 2008.

Stop 6: Tibetan Refugee Centre
Situated at Lebong, and locally known as the Hermitage, the Tibetan Refugee Self Help Centre (TRSHC) was started by Mr. Gyalo Thondup through local charity on 2 October 1959. Initially it provided emergency relief to Tibetan refugees who came over from Tibet during the period, following a difficult trek across the Himalayas. Tibetans considered the place auspicious because the Thirteenth Dalai Lama had spent his exile years here between 1910 and 1912. Presently the Centre provides shelter to several needy Tibetan families, runs pre-schools for small children, and a primary health care centre. It also provides technical training on handicrafts, etc.

Stop 7: Himalayan Mountaineering Institute and Tenzing Rock
The Himalayan Mountaineering Institute was founded on 4th November, 1954, after the first ascent of Mount Everest by Tenzing Norgay, an Indian and Edmund Hillary, a New Zealander, in 1953. Darjeeling being the home town of Tenzing Norgay, the Institute was established at Darjeeling, and Norgay was appointed its first director. It has now become a centre of excellence in the field of mountaineering. Originally the Institute was opened at Roy Villa on Lebong Cart Road, which was earlier the residence of a great Indian scientist, Jagadish Chandra Bose, and where Sister Nivedita, one of the greatest disciples of Swami Vivekananda, had spent her last days. In 1958 the Institute was shifted to its present location on Birch Hill, from where one can have majestic views of Mt. Kangchenjunga.
Near the Himalayan Mountaineering Institute lies the Tenzing Rock, a huge rock that has been named after Tenzing Norgay. Another giant rock nearby has been named as Gombu Rock to commemorate Nawang Gombu’s ascent of the Mt. Everest twice (in 1963 and 1965). This was the first time a person climbed Mt. Everest twice. Nawang Gombu was a nephew of Tenzing Norgay, and became the director of Himalayan Mountaineering Institute after the retirement of Tenzing Norgay in 1976.

Day 4: 15/11/2017
Darjeeling to Siliguri (via Kurseong)
Stay at Siliguri.

The route from Darjeeling to Siliguri will be through Sonada where the headwater area of Balason River valley is cut in Darjeeling gneisses. Down the road one sees several tea gardens along the hill slopes, as well as some areas of land slips and debris flows with a very thin forest cover. The road passes through many gullies with large boulders. The cross sections of the road and the railway bridges are too small to accommodate the high discharge of debris moving frequently through them, and therefore cause damage to these infrastructures.

The route will also pass through Kurseong town, a trading and administrative centre. After passing through the imposing rocky wall of Eagle Craigs, Kurseong town is reached on the southern and eastern slopes of the first ridge at an elevation of 2000 m a.s.l., which is known as the Mahaldharam Range, or the Dow Hills. This ridge is built of the more-resistant Darjeeling Gneisses. Yet, high deforestation on its southern margin and exposure to heavy monsoon rains exceeding 4500 mm per year makes the slopes vulnerable to landslides. During the rainstorm of October 2-5 1968, Kurseong received 1091 mm rainfall.

Stop 1: Ambootia Landslide
This is an interesting landslide zone in the Darjeeling Himalayas. On October 2–5, 1968, consequent upon an extreme rainfall event, hundreds of earth flows, debris flows, and large landslides scarred the mountain slopes in the area (Starkel, 1972). It has been estimated that between October 2 and 5, 1968, Darjeeling Himalayas experienced 600-1000 mm rainfall within a span of 50-60 hours. Ambootia recorded 890 mm rainfall, while an automatic rain gauge at Nagri Farm (6.5 km north of Ambootia) recorded a rainfall intensity in excess of 50 mm per hour (Starkel, 1972) during the last four hours of October 4. The largest of the landslides occurred along the left side of the Balasan River valley in the Ambootia Tea Estate, where the river cuts through an E-W marginal ridge rising to 1200–1800 m above sea level (Fig. 12). The Polish researchers working on this landslide termed it as a “landslide valley” because the landslide not only has the shape of a valley, but its evolution is also the
product of gravitational slope processes acting in conjunction with linear down-cutting (Froehlich et al., 1991, 1992). The surrounding area is formed of the Darjeeling group of metamorphic rocks, comprising gneiss, mica-schists, and chlorite-schists of various resistance, inclined 30–50º NNW. The rocks are deeply weathered and the high density of fractures in the area is most likely indicative of a high degree of seismic activity.

During the 1968 event, thick saturated colluvia and the underlying weathered rocks in the shallow valley head slumped down and spread out like debris flow, carving out a channel 30–60 m deep and pushing out a mass of 10–15 million cubic m. Some of the material got deposited in the form of a fan in the Balasan River bed. The debris fan formed a dam. As a result, a lake several km long was also formed, storing about 10 million liters of water. The undercutting of the right side of the landslide in its middle part, featuring several hummocks, led to large rock falls. On the opposite side, shallow pene-structural earth flows and slips were triggered at the same time. We do not know the extent of the transformation that took place in October 1968, as the first photographs, drawings, and written records only became available in 1983 and 1984.

Subsequent transformation included a continuous retreat of the right side niches, supplied by groundwater from a colluvial aquifer, as well as an extension of shallow slips and the formation of deeper cracks on the left slope. A simultaneous deepening of the main channel by debris flows led to the undermining of the upper part and the dissection of the lower part of the valley sides by new chutes and slips (Fig. 13).

Fig. 12.
Location of Ambootia landslide valley in the Balasan River catchment.
1 - each 500 feet contour line;
2 - landslide valley;
3 - tea factory and bungalows.
In March 1983, the main upper landslide niche resembled an amphitheatre, with its edge reaching probably no higher than 980 m above sea level. All area slopes had fresh features. At the outlet of the main valley, a large colluvial fan was found to be completely without vegetation. This suggested that at least prior to 1983-84 the landslide might have been very active (Fig. 14). In 1988, this Ambootia landslide at the southern edge of the Tea Estate got reactivated again due to a
high rainfall event. The landslide was very active from 1968 to 2003, when it continued to develop sequentially. However, since 2003 it is gradually becoming stabilized (Fig. 15).

Fig. 15.
Stabilization of the landslide:
In March 1995, an “Eco-development Plan for the Ambootia Tea Estate for 1996–2000” was prepared. The plan included different types of watershed protection strategies such as the reforestation of the landslide and surrounding area using selected plant species, avulsion of water, check-damming, gully plugging (especially in the main “khola”), and grazing restrictions on landslide-prone slopes. The program went into effect in 1996. The upper section of the creek had already been re-routed in the 1980s. Hence the widest colluvial part had already ceased to retreat, as was estimated from photographs taken in different years. The years that followed were very wet once again. In 1998, 4229 mm rainfall was recorded, with highest monthly rainfall of 1505 mm and highest daily rainfall of 335 mm. The right bank of the upper part of the landslide slumped again and became dissected by a number of new gullies. The wetter years, combined with grazing restrictions, facilitated the re-vegetation of many parts of the bare slopes. The revegetation process could be easily observed across the area. Moreover, several debris dams were constructed along the main river channel in 1998-99. Following a wet 1999, the active parts resembled almost like in the year before. In 2002, an Organic Biodynamic Research Centre was established close to the landslide area, with a nursery of tea bushes and trees, which were continuously planted along the northern edge of the landslide. In February of 2003, following a relatively dry 2002, the number and area of slips decreased again. In March of 2004, while revegetation continued to make progress, several small parts of the landslide became reactivated, most likely due to higher rainfall in the summer of 2003. The annual rainfall was 3879 mm and July rainfall was 1219 mm. The following two rainy seasons (2004 and 2005) were characterized by very low precipitation (2447 mm and 2617 mm, respectively). Virtually the entire landslide area, except for small vertical slope sections, was covered by dense vegetation, young forest species, and a dense carpet of grass. Only the main gully, which collects water during rainstorms, transported coarse debris. Over the course of the next three years (2006 to 2008), annual rainfall increased to about 3000 mm, but with no major rainstorms. Re-vegetation continued to make progress and only small slumps could still be observed on a number of steep slopes. Presently most part of the landslide has been stabilized.
Stop 4: Paglajhora Slump Valley
Perhaps, the largest and the most complicated among the landslides in the Darjeeling Himalayas is the lower Paglajhora slump valley, which is active since the severe 1950 rainstorm. The morphological configuration of the Paglajhora slump valley is controlled by its geological structure and remodelled by the local hydro-geomorphic processes. The slope forms exhibit a combination of convex – concave – irregular profiles with highly variable inclination (10° to 35°). Overland flows, feeding the uppermost niche during heavy rains, get transformed into concentrated subsurface flow over the permeable colluvium. The observed rills and cracks facilitate piping and deep drainage towards the slumped areas. The high intensity rainfall, as well as the high relative height and steep gradient, make efforts to stabilize the Paglajhora slumps difficult (Fig. 16). At present, the slump’s form has reached a quasi-unstable equilibrium. Each extreme rainfall (above 300 mm/day) causes substantial changes in its morphology (Sarkar, 2011).

Fig. 16.
Shib Khola slump basin (after Sarkar, 2011).
Slope instability in Paglajhora is essentially a style of adjustment of the natural hydro-geomorphic processes operating on colluvial slopes and under the condition of unstable equilibrium. The extreme rainfall events hasten the transformation of slopes and river channels, and are followed by the formation of regoliths and armouring of channels. The catastrophic landslides tend to push the overburden down the slope, but need a relaxation and transformation time to move the sliding masses (Fig. 17).


*Fig. 17.*

*Panoramic view of the Paglajhora slump valley.*
Stop 5: Tindharia Landslide (800 m a.s.l.)

At Tindharia, as also at many other places, the hill slopes formed of Damuda Shales and Daling Phyllites with quartzite beds have become moderately undermined by the activities related to the construction and maintenance of the old railway tracks and the Hill Cart Road, even though efforts are made to stabilize the slopes mechanically. At places these unstable slopes are liable to various types of shallow mass movements (Fig. 18), often damaging the railway tracks and the roads. During the October 1968 rainstorm, the Hill Cart Road was blocked at more than 200 places. Basu and Sarkar (1985) described in details some such slides formed after the heavy rains of 1982 and 1984. All these slides on the undercut deforested slopes develop mainly after several consecutive heavy rains, and often at the end of the rainy season, when the crossing of the saturation and plasticity thresholds of the materials lead to slope failure.

Fig. 18.
A landslide along the railway tracks and the road at Tindharia, which was formed in 1982 (after Basu & Sarkar, 1985).
Stop 6: Sukna (300 m a.s.l)
At Sukna two flat old terraces occur at about 300 m and 120-150 m above the active flood plains. Along the road crossing under the Sal (Shorea robusta) forest, deeply weathered gravels and boulders of metamorphic rocks are found exposed, with well-developed tropical red soil on the top. The higher surfaces belong to the tectonically-raised blocks situated between the Main Boundary Fault MBF) in the north and the Himalayan Front Tectonic Line (HFTL) in the south (Nakata, 1972).

Day 5: 16/11/2017
Siliguri to Kalimpong
Stay at Kalimpong.

Stop 1: Sevok – Tista Valley (170 m a.s.l)
Sevok is a small town and an important crossing point of the swift-flowing Tista River through a robust bridge. Here the river is 60-80 m wide, and flows through a deep rocky canyon, undermining both its valley sides. The channels are separated by a number of gravel bars with boulders of 1-2 m dia. Normally during floods the water level in the river rises by about 5 m, as marked by sandy over-bank deposits and lack of vegetation on the slopes. During the high-rainfall event of October 1968 the water level along the Tista River at Sevak rose by 25 m, which washed away the bridge. It is estimated that the river discharge at Sevak was approximately 18000 cumec. This exceptionally high discharge was accompanied by landslides along the hill slopes and consequent debris flows into the river channel, which caused temporary damming of the river at several places. Since then the bottom of Tista River was lowered by 1.5 m.

Stop 2: The Lish and the Gish Rivers
After crossing the bridge at Sevak, the road passes through the Lish River and the Gish River, which are two important tributaries of the Tista River. The morphology of the two rivers and geomorphic features of their surroundings will be observed near the road bridges on the two rivers.

Lish River catchment: Lish River is only 20 km long, and drains a total area of 64 sq. km, out of which 48 sq. km is under the hills with a peak of 1820 m. A dendritic network of deep valleys has cut into various geological units from the Siwaliks to the Darjeeling Gneisses. Between 1930 and late 1990s the area occupied by forest was reduced from 45% to 31% and at the same time the area occupied by agriculture and settlement increased from 16.75% to 45.5%. One important land use in the catchment area is coal mining. Data from 2004 reveals that the area covered by landslides has increased from 1.5 sq. km to 5 sq. km (Sarkar, 2012).
An alluvial fan, with a length of about 10 km and width of 3-5 km, can be noticed beside the bridge of the National Highway. Its surface descends from 200 m to 120 m. There are many records of floods and damages, during which the braided channel widened to 1.5 km in the upstream of the bridge, and to 1 km downstream (Fig. 19a). In the 50-year period between 1930 and 1980 two large floods occurred in this catchment during 1954 and 1968. The first one considerably damaged the road bridge, while the second one washed away the bridge. Considerable damage took place in the Bagrakote and Washabari Tea Estates. In 1968, Bagrakote recorded 809 mm rainfall in 3 consecutive days, the highest being on 5th October when 499 mm was recorded.

Mapping of the channel features along the Lish River from satellite images of 1990 and 2004 showed extensive bar and shoal formation, but did not reveal any major changes in their spatial dimensions (Fig. 19b). However, a tendency towards aggradation and bank failure could be identified. Field work suggested that the channel floor of the river was elevated by 2.5 m between 1982 and 2004. Comparing features drawn from old and new maps and satellite images suggested that the total surface area covered by bars and shoals along the Lish River increased from 11.4 sq. km in 1930 to about 19 sq. km in 2004 (Sarkar, 2012). During the recent past three floods were recorded in 2002, 2005 and 2007.
**Gish River catchment:** Gish River drains a larger catchment than the Lish River. Out of its 201 sq. km area, 160 sq. km is located in the hills. The river is 41 km long, out of which more than 30 km is in the hills. The dendritic drainage pattern has been formed on the same rocks described for the Lish River catchment. The highest ridge in the headwaters rises to 2370 m. Like in the Lish River catchment, this catchment area is also under coal mines, and is undergoing deforestation. Many large landslides are located especially in the marginal parts of the hills (Sarkar, 2012).

The area covered by forest between 1930 and late 1990s has decreased here from 49% to 37% of the total land use area, while agricultural land plus settlement area has increased from 22.6% to 33.6%. The extension of braided pattern followed between 1930 and 1980 when three creeks at the outlet from hills starting from 195 m have formed a fan of 3 km width. In 1954 a devastating flood occurred, when about 10 sq. km area of cultivated land was flooded and up to 1 m silt layer was deposited.

Satellite images of 2004 revealed that aggradation extended upstream and the area of non-vegetated bars and shoals was reduced. This was visible especially in the apex part of the fan where hundreds of trees got buried under sand and gravel bars. Between 1982 and 2004 the channel bottom rose by about 2 m, but many patches became re-vegetated, especially downstream of the two bridges and up to the junction with Tista River, due to gradual incision of several branches of the channels. The width of the lowest course of Gish River channel was reduced from 2 km to about 0.5 km (Sarkar, 2012).

**Stop 3: Kalijhora – TLDP Stage IV**

**Stop 4: Rambhi – TLDP Stage III**

**Human role in shaping the hydromorphology of Tista River**

Łukasz W., A. Bucała and S. Sarkar (2014) attempted to evaluate the hydromorphological state of Tista River and to determine the role of human activity in shaping the hydromorphology. The field research was carried out in selected channel sections with and without noticeable human interference. The assessment of the hydromorphological state was conducted on the basis of the River Habitat Survey method.

The analysed sections of the Tista River with noticeable human interference, i.e. river bank modifications, were found to be characterized by small or considerable modifications of the river habitat. The modifications that involve concrete walls or river bank re-profiling occur in the long channel sections, and their function is to protect the road infrastructure and buildings from river erosion. Despite a large human impact on river bank morphology, the studied channel sections of Tista River
are characterized by considerably large diversification of natural morphological elements. As a result, the river habitat quality is not significantly different from the habitat quality in the sections without noticeable anthropogenic pressure, and can be categorized as low or sufficient. Additionally, exploitation of gravel during the dry season takes place at many places (Lukasz et al., 2014).

Two reservoirs between Kalijhora and Tista Bazar, TLDP Stage III & TLDP Stage IV, which are under construction, will be another important factor leading to modification of the morphology in the mountain section of the Tista. The construction of reservoirs may cause the disappearance of some hydromorphological features of the valley that are characteristic of a river, and may result in the development of conditions typical of standing waters. The operation of reservoir complex will most likely have an influence on the natural hydrodynamics of the channel and on the fluvial processes. Below the reservoirs, it can be expected that erosion of the channel bottom caused by the outflow of water without river debris will increase. Intense accumulation of the material transported by Tista River will take place in the reservoirs. The local community that exploits the fluvial material in the area of the reservoir, having no access to the channel, as it is presently under standing water, has begun exploiting gravel in terraces located high above the channel. It should be assumed that, after some time, this will cause permanent changes in the morphology of the higher parts of the valley, and will also lead to other land-forming processes like landslides.

**Stop 5: Tribeni Confluence at Pesoke (615 m a.s.l.)**

At Pesoke, the view of the Rangit River meeting the Tista is an unforgettable treat for the nature lovers. The Rangit with its deep green and crystal clear water gushes in and meets the forceful mountain stream Tista at a point called Triveni. A closer look reveals that a fan is forming at the Tribeni confluence of the three rivers, the Tista, the Rangit and a small river, the Pesoke.

**Day 6: 17/11/2017**

Kalimpong to Bagdogra Airport
Bagdogra Airport to New Delhi
Stay at New Delhi.


In collaboration with

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For Young Geomorphologists

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A1: Geomorphological Field Guide Book on DECCAN INLAND

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Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
## Geomorphological Field Guide Book on Deccan Inland (30 October - 5 November, 2017)

### Itinerary

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A. THE DECCAN TRAP REGION:
AN INTRODUCTION

The ‘Deccan Inland’ (also known as the Deccan Trap) is essentially a basaltic plateau within the Peninsular India, covering an area of about half a million square kilometres. The huge thickness of extruded basalt about 65 million years ago masked a pre-existing landscape, dominantly on granite-gneiss, and is intercalated with numerous ash beds. The western edge of this vast tract is marked by a ~1500-km long escarpment facing the Arabian Sea, called the Western Ghats, from where the plateau has a gentle eastward tilt, and is dissected by numerous streams of the Godavari and the Krishna River basins, which drain into the Bay of Bengal. The eastern edge of Deccan Trap is marked by a series of discontinuous hill ranges, called the Eastern Ghat. Occurring to the east of the Western Ghat escarpment, a large part of the Deccan Trap country falls within the rain-shadow zone of the South-west Monsoon (June to September), which is the main rainy season over most part of India. Deccan Trap area is dominated by a semi-arid climate, with a mean annual rainfall of 600-900 mm. The Western Ghat, though, receives copious rainfall of more than 2000 mm. The difference is reflected in the overall rugged topography of the plateau with a skeletal soil, sparse vegetation and a stony look vis-à-vis the lush green slopes of the Western Ghat. Deccan Trap occupies the whole of the state of Maharashtra and small parts of the neighboring states such as Saurashtra Region of Gujarat, Malwa and Mandla Region of Madhya Pradesh and small parts of Karnataka and Andhra Pradesh.

The tour will be entirely within the state of Maharashtra, where the mean summer temperature varies roughly from 30°C to 40°C, while the mean winter temperature varies from 10°C to 12°C, with wide spatio-temporal variation. Rainfall occurs between June and September and there is enormous variation in the amount across the state. The coastal areas receive above 7000 mm of rainfall annually at many stations, and on the plateau top, it is about 5500 mm annually. At Mahabaleshwar on the Western Ghat, the mean annual rainfall is 5761 mm. After one descends from the Ghat, Pune and Aurangabad receive about 700 mm rainfall annually. Further to the east, the central part of the state suffers from rain-shadow effect. A large part in the central Maharashtra has a semi-arid climate with a mean annual rainfall of 400 mm or less. As one proceeds eastward, the amount of rainfall increases again under the influence of Bay of Bengal. Nagpur receives about 1000 mm annually.
Basalt-derived soil, locally known as "Regur" or black cotton soil, characterizes the whole of Maharashtra state. In order to better appreciate the landscape of the Deccan Trap to be visited (Fig. 2), we first provide a brief geomorphological background of the terrain, as well as a short description of other aspects of the region, including people, their livelihood, major land uses, etc.

Fig. 2.
Landsat ETM + Mosaic Images of the state of Maharashtra, showing the sites to be visited during the excursion and the routes to be taken.
Deccan Trap region is the third geologically important huge continental basalt province in the world besides Parana Province of Brazil and the Karoo Province of South Africa. The Trap region covers an area of about half a million square km and forms a major geomorphic and morpho-tectonic unit of the Indian Subcontinent.

The Deccan Trap basalts were erupted about 60-65 Ma ago during the separation of the Seychelles micro-continent from India (Widdowson and Mitchell, 1999). This rifting occurred during the northward movement of the Indian subcontinent as it passed over the Reunion Hotspot. On a regional scale, the traps are 3000 m thick. Based on the chemo-stratigraphic and palaeomagnetic studies it is divided into three sub-groups, the Kalsubai (oldest), the Lonavala and the Wai (youngest) formations (Beane et al., 1986; Devey and Lightfoot, 1986; Subbarao and Hopper, 1988; Mitchell and Widdowson, 1991; Subbarao et al., 1994; Subbarao et al., 2000). The older flows (Kalsubai) occur in the northern part around Nashik and the younger flows progressively overstep southwards. The youngest flows (Wai) are the most extensive and widespread. Early Tertiary laterites are developed on these younger flows and are almost absent on the older flows occurring in the northern part.

The western part of the Trappean landscape is marked by a huge, impressive erosional escarpment known as the Western Ghats or Sahyadris in India. Many of the rivers are allochthonous and occupy unusually large, misfit valleys. The river channels are deeply entrenched in bedrock or alluvium, and flood plains are almost nonexistent. Many of the channels display channel-in-channel morphology.

Floods occur during the active monsoon season, and especially during the rainstorms originating over the Arabian Sea or the Bay of Bengal. Very rarely, these flood events are regionally synchronous due to the large geographical area.

The most striking features of the Trappean landscape over the plateau top are stepped hills and ranges, wide box-shaped valleys and large gently-sloping denudational surfaces occurring on the main divides (Kale and Gupte 1986). Hill slopes and valley bottoms are featured by weathered basalt (locally known as murum), regolith, colluvium and black soils (vertisols). Alluvium is confined to narrow belts close to the river channels.
Laterites
Laterite is the only widespread post-Traps and Tertiary geological formation occurring in the region. Laterites have been the subject of study for about 200 years since Buchanan introduced the term laterite in 1807 to describe Fe-rich material that gets hardened on exposure to air. Genetically, Trap laterites have been classified as ‘primary’ (bedrock-derived and in situ) and ‘secondary’ (transported and reworked, or detrital) laterites. On the basis of altitude and geomorphic situation these are also classified as ‘high-level’ (on the Ghat crest) and ‘low-level’ laterites (coastal) (Fox, 1923). The high level laterites occur in the Western Ghat zone on the highest peaks and form the highest topography in the southern part of the Trap region. Laterites have a gentle slope towards the east and southeast. Patches of laterites are also present in the semi-arid region, such as Khanapur and Jath. During the excursion, it is proposed to stop at a few sites to appreciate the laterite beds and the lateritic landforms.

Coastal or low level laterites are developed over the Deccan Traps (Cretaceous-Eocene) in the north and over Archaean and Proterozoic rocks in the south (south Konkan, Goa and Karwar). There is enough evidence to suggest that not all the laterites in south Konkan and Goa are developed on bedrock. Some of them have formed due to the laterisation of alluvium also.

Low-level laterites form coastal plateau dissected by the west-flowing short streams that have deeply entrenched the laterites. These laterites of the coastal zone occur along a wide zone at the foot of the Ghat, but the escarpment section is devoid of this formation. The coastal laterites have a gentle seaward slope (Widdowson and Gunnell, 1999). Unlaterised hills rise above the lateritic surfaces, indicating that the process of laterization was confined to the low-lying plains.

Based on the ages of laterites, Widdowson and Gunnell (1999) proposed that these laterites had been formed much before the onset of monsoon climate over the Indian subcontinent (ca. 8 Ma) and thus were formed under a totally different climatic and perhaps hydro-geomorphic condition.

Quaternary Alluvial Record
The current Trapean landscape is essentially erosional in nature, with near-absence of Tertiary and early Quaternary sediment records (Kale and Rajaguru, 1988). Late Quaternary deposits however occur in many river valleys that include alluvial deposits along the main rivers (Kale and Rajaguru, 1987), colluvial deposits in the foothill zones of the divides (Joshi and Kale, 1997) and calc tufa deposits on the valley sides (Pawar et al., 1988).
Alluvial deposits in the Deccan Trap region are modest in terms of lateral and vertical extent and are confined to a narrow belt along the river channels. A large number of radiometric dates indicate that for several thousand years, a succession of aggradational and excavational episodes followed one another in response to Quaternary climatic changes (Atkinson et al., 1990). Although spatially variable, the last major phase of aggradation was associated with the late Pleistocene aridity, and incision occurred in response to the early Holocene strengthening of the southwest monsoon (Kale and Rajaguru, 1987; Atkinson et al., 1990; Rajaguru et al., 1993). Alluvium and river terraces are less important elements of the Konkan landscape. Owing to their location, sea level changes have primarily determined the river behavior during the late Quaternary period (Kale and Rajaguru, 1988).

Archaeological and palaeontological studies indicate that during late Quaternary period, the upland region was characterized by tropical grasslands. Animals like cattle, horses, deer, elephants, ostrich, hippopotamus and rhinos roamed over the landscape. Stone Age artifacts are widespread in the upland region and indicate that the Early Man was present in the Deccan volcanic province since the Acheulian time.

**Socio-economic Aspects**

As stated above, the field trip will be confined within the state of Maharashtra. Maharashtra occupies 307731 km$^2$ area, which is 9.84% of the total geographical area of the country. Its total population is about 112.4 million, with an average density of 365 persons per km$^2$ It has a sex ratio of 925 females per 1000 males, which is lower than the national average, i.e., 940 females per 1000 males. Though the state reveals a lesser population density of 365 per km$^2$, as compared to the national average of 382 per km$^2$, there is wide disparity in its distribution across the state. There are 378 urban centers and 41000 villages within the state. Mumbai and Thane districts have densities of 20980 and 1157 persons per km$^2$, respectively, while Ahamadnagar district has 266 persons per km$^2$. Pune and Aurangabed districts, where most of the tour sites are located, have population density of 608 and 366 per km$^2$, respectively. According to the 2011 census, literacy rate of the state is 83.2%. Female literacy is 75.48%, while male literacy is 89.82%.

Agriculture is the main occupation in the state in spite of it being the most industrialized state in the country. Like any other part of the country, agriculture is heavily dependent on the vagaries of the summer monsoon. The other major constraint is an overall shallowness of the soil. Since basalt-derived vertisol soil, locally known as "Regur" or black cotton soil, is dominant, the soil is clayey, rich in iron but poor in nitrogen.
It is suitable for cotton cultivation. Principal crops are rice, jowar (coarse millet) and bajra (pearl millet). Wheat, pulses, onions and vegetables also constitute main crops of the region. Sugarcane, cotton and turmeric are the main cash crops, while several oilseed crops, including sunflower, groundnut and soybean, are also grown extensively. The state is famous for Alphonso mango, which is exported in large quantities. Banana, grape and orange are also important fruits of the state, and fetch the state considerable revenue.

Large parts of Deccan Trap are characterized by a shallow rocky terrain, with poor natural vegetation cover. Consequently, open scrubs abound. Forests occupy only 17% area of Maharashtra state, confined mostly to the Western Ghats and the eastern hill ranges, while the plateau tops are dominated by open scrub jungle. Mumbai is the capital of the state which is the largest city and the financial capital of the nation. This is one of the most developed and the wealthiest of the states in India, contributing 25% of the country's industrial output and 23.2% of its GDP.

Maharashtra is India's leading industrial state. Nearly 46% of the Gross State Domestic Products is offered by the industrial sector. Mumbai Metropolitan Region (MMR) has historically been the most industrialized area in the state, followed by Pune Metropolitan Area, Nashik, Aurangabad and Nagpur. The state has had a long history in textiles, with the state capital Mumbai being one of the original homes of India's textile mills. The six important industries in the state are cotton textiles, chemicals, machinery, electrical appliances, transport and metallurgy. Pune is one of the largest automobile hubs in the country. Sugar industry has made considerable progress, especially in the co-operative sector.

Among the most populous first-level administrative country subdivisions in the world, Maharashtra stands second in the list. Within India, the level of urbanization is the highest in Maharashtra (45.23%), which is well above the nation’s average (31.16%). Mumbai, with a population of 18.4 million, is the largest metropolis in India. Next to Mumbai, the other large cities in the state are Pune (5 million), Nagpur, Pimpri-Chinchwad, Nashik, Navi Mumbai, Dhule, Aurangabad, Parbhani, Akola, Kolhapur, Thane, Solapur, Amravati, Nanded and Latur.
Day 1: 30/10/2017
Delhi to Pune by Flight
Stay at Pune.

The first day of the tour will be spent on discussing the routes of the field trip, the logistics, and the general characteristics of the area. The field trip will begin from Pune, and will conclude at Aurangabad (near Ajanta caves), spanning a distance of 875 km. During this period it is proposed to take several transects across the Deccan Trap to observe some of the major landforms as well as some typical geomorphic features on basaltic terrain, and discuss their salient characteristics. An idea of the broad topographic variability in the region and the major streams flowing through it could be had from Fig. 3.

**Fig. 3.**
A DEM of Maharashtra state, showing the broad landscape variability in Deccan Trap Region, as well as the major stops during the excursion (Inset Map of India with the state boundary and the current Deccan Trap boundary).
Day 2: 31/10/2017
Pune to Panchgani and Mahabaleshwar via Wai and Sendurjane (125 km; all distances are from Pune, unless specified)
Stay at Mahabaleshwar.

It is proposed to begin the excursion with a visit to the south-western part of the Deccan Trap terrain, especially to appreciate landscape evolution along the Western Ghat area within the Krishna River basin. The road from Pune to Wai passes through a rugged and almost desolate basaltic tableland with shallow soils, and dissected by numerous ephemeral streams that join the Bhima River, a major tributary of the Krishna River.

Stop 1: Wai-Sendurjane Colluvial Deposits (88 km)

This site provides the view of a typical colluvial deposit occurring along the foot of the hill slopes in this upland area, and forming the interfluvces of the numerous stream catchments. The site is located near Sendurjane village on the northern side of the Surul-Wai-Mahabaleshwar road. Currently the deposits are deeply disturbed by various activities of human that includes stone quarrying, agriculture and construction.

Geographically, the site falls in the source region of the Krishna River which is a major river of Deccan Peninsula. The colluvial deposits drape the foothills of one of the offshoots of the northern divide of the Krishna River. Although the site is close to the Western Ghat Escarpment, it falls in the rain shadow zone and receives about 800 m rainfall as compared to 6000 m in the adjacent Ghat Zone.

The hill range behind the deposit has an average elevation of 1000 m above msl, with the highest elevation reaching 1184 m above msl. The colluvium-draped pediment extends for a distance of about one km. The average elevation of the pediment is about 750 m above msl. The local relief ranges from a few tens of meters to more than 425 m. The deposits overlie the rocky pediment on basalt, and are thinner near the foot of the hills. The thickness reaches a maximum of >5 m in the middle part, and becomes thinner again downslope within a distance of less than one km to merge with the black soil/alluvium. The areal extent of the deposits at this site is approximately 6 km².

A dense network of gullies has dissected the deposits. These gullies are sinuous and generally v-shaped. Inter-gully areas are large, flat and smooth. Many gullies are incised through the colluvium and into the underlying basalt bedrock, which is highly weathered. Active gully-head erosion is witnessed in the form of knicks. The higher order gullies/streams meet the main river Krishna after traversing a distance of approximately 4 km.
Texturally, the colluvial sediments are dominated by coarse silts (4-5 Ф) and the mean phi value is 4.2 (Joshi and Kale, 1997). Skewness is positive and indicates excess amount of finer fractions. Sorting is poor. SEM studies of a few grains indicate v-notches, chatter marks, high surface relief, considerable etching and precipitation on the grains. All these features provide evidence for the role of fluvial activity, short-distance sediment transport and diagenesis. Smectite is the dominant clay mineral in these sediments (Joshi and Kale, 1997).

All through the deposits, calcrete occurs profusely (CaCO₃ range: 12-70%). The Si/Sesquioxide ratio ranges from 1.0 to 1.5 as compared to 2.1 for fresh basalt rock, and suggests weathering of the deposit (Joshi and Kale, 1997).

As could be observed, the surrounding landscape is rarely in pristine, natural state, and is disturbed by human activities in varying degrees. The impacts of these activities can be seen in the form of numerous cuts and fills, as well as over-burdens. We shall, however, stop at one or two naturally cut exposures in a gully to observe a few litho-sections. The sections reveal that calcrete-rich fissured clays occur at the base. Several gravelly units of varying thickness overlie this unit. Evidence of scour and fill are present in the middle level. Finer but gravelly units occur at the top. Mud balls could be seen at some places. Upward fining sequence can be detected within some units. Calcium carbonate is conspicuously present in all the units.

The presence of clays at the base suggests deposition of fines in a shallow basin environment or in a wetland condition under semi-arid climate. The overlying gravels suggest that the deposition of the fines was followed by a sudden flux of coarse gravel by short ephemeral streams. Frequent alterations of sandy/silty facies with coarse gravel suggest the erratic nature of the depositing medium. The scour and fills are clear indications of dominant fluvial activities bringing the sediments down the hill slopes. The unsorted nature of the gravels and rapid changes in the facies indicate highly variable runoff and discharge conditions at the time of deposition. The presence of mud balls suggests that the deposition was not continuous but was interrupted by short periods of erosion and cutting. Calcrete formation post-dates the deposits. A single U/Th date on a calcium carbonate nodule from a gully yielded an age of 75 ka, indicating that these are relict deposits and that the bodies of colluvial silts can persist for tens of thousands of years in this area (Atkinson et al., 1990). This and a few more dates from other colluvial sites imply that the deposits might have been laid down during a major glacial aridity. Evidently, the materials had to be formed through weathering of hill slopes under a wetter climate (perhaps last interglacial). Strengthening of the southwest monsoon during the early Holocene period (Kale and Rajaguru, 1987) perhaps stopped any further addition to the deposits.
Increased runoff and consequent gully formation led to erosion and remobilization of the sediments. Although currently in a disturbed state, the flat and large inter-gully areas suggest that the deposits are being removed very slowly.

From this stop, we proceed towards Panchgani-Mahabaleshwar via Wai town. We cross the Krishna River near Wai, and then start ascending the Pasarni Ghat, which offers a breathtaking view of the Krishna Valley. The scenery begins to change dramatically from a tree-less, dry rocky terrain to greener lateritic terrain. We reach the next stop, Panchgani (102 km from Pune).

**Stop 2: Panchgani Tableland (102 km)**
Panchgani is one of the most visited tourist destinations in Maharashtra state. The settlement here was founded by the British in the mid-19th Century, and developed as a popular health resort. The most prominent geomorphic features here are the isolated, laterite-capped tablelands and the mesas, which rise abruptly from the surrounding plains. The special identity of Panchgani laterite is its flatness, vastness and simplicity (Kale, 2014). Thick laterite crust (ferricreted duricrust) acts as the cap rock and protects the underlying Deccan Trap basalt flows from surface erosion. The elevation of the mesas varies between 1300 m and 1350 m above msl. The edges are sharp, with vertical cliffs of 5 to 25 m height. Five such mesas can be noticed at Panchgani, and hence the name “Panchgani” (i.e., five entities). The mesas are separated by valleys of the Bavdhan River and the Kudali River. The local relief is generally less than 550 m. Panchgani falls in the rain shadow zone of the Western Ghats, but receives an average annual rainfall of 1700 mm. At Mahabaleshwar, the rainfall exceeds 6200 mm.

The mesa tops have negligible relief and have a general slope toward the south and southeast. A number of pseudo-karstic features, such as large depressions that are filled with wind-blown sediments, sinkholes, natural bridges and caves, are associated with the indurated laterite crust (Kale, 2000). Their development is favoured by the occurrence of an impervious, clay-rich lithomargic horizon below the vesicular and porous laterite crust. All along the cliff margins, large blocks have been peeled off from the main tableland, providing an example of mechanical disintegration of the hard indurated crust on the top. The disintegration is caused by undermining at the base of the indurated layer, followed by caving. Consequently, as soon as the laterite cap is stripped, the saprolite horizon gets eroded, giving rise to smoother and gentler slopes (Kale, 2014).
Duricrust distribution: Dissected high plain or inversion of relief?
The present distribution of high-level duricrust on Western Ghats has been under speculation for quite some time. The views can be grouped under two schools of thought: (1) a ‘high-level model’, and (b) an ‘inversion of relief model’ (Fig. 4).

(a) High-level model: Formation of a vast and continuous blanket of laterite, and then erosional destruction of most of it to leave the ferricretes at mesa tops (Kale, 2000). The author suggested that the roughly-accordant ferricrete mesas around Mahabaleshwar were the remnants of a once-continuous (but now largely destroyed) ferricrete blanket on the lava pile.

(b) Inversion of relief model-1: A lava flow fills a valley; original streams are shown as dashed lines. New lateral streams form on each side of the lava flow, and down-cutting and valley widening by them leave a lava mesa (Ollier, 1988).

(c) Inversion of relief model-2: The floor and lower slopes of a river valley are partly covered with alluvium and colluvium, which are cemented to form ferricrete. Later, erosion attacks neighbouring weathered rock and the resistant ferricrete forms mesas (Pain and Ollier, 1995; Ollier and Sheth, 2008).
It has long been suggested that these laterites have developed from the topmost exposed flows of the Deccan Trap across a vast plain (Widdowson and Cox, 1996; Widdowson, 1997; Kale, 2002). This acted as a continuous blanket over the basalt topography, but subaerial denudation since then has left the remnants of the laterite-capped plains as the ferricreted mesa tops. The above authors suggested that the roughly accordant ferricrete mesas around Mahabaleshwara were the remnants of a once-continuous (but now largely destroyed) ferricrete blanket on the lava pile. Palaeo-magnetic considerations suggest the late Cretaceous – early Palaeogene as the most likely age of these laterites (Schmidt et al., 1983). In Panchgani area, the laterite-capped mesas are found on interfluves and occur on both sides of the river valley almost at the same elevation. The present-day laterite distribution and the broadly accordant heights of the hills suggest that the mesas are erosional remnants of an earlier vast laterized surface over a large part of Deccan Trap – several tens of kilometres from Mahabaleshwara (which is located at a higher level in the west) in all directions. Subsequently the laterized surface was breached, first by headward erosion of the streams and then by vertical incision, followed by lateral extension of valleys. This created an uneven surface where laterite-capped outliers stood higher above the surrounding areas as mesas and tablelands.

Pain and Ollier (1995) and Ollier and Sheth (2008) suggested the formation of duricrusts along drainage lines, followed by inversion of relief. They suggest that the ferricrete caps forming the present summits of the duricrusted mesas today were formed in a river valley system, and these original valleys have since been inverted as the surrounding softer weathered basalts have been eroded to a greater extent. The chief line of evidence in support of this relief inversion hypothesis is the thin shoe-strings-like appearance of the outcrop mesas, occurring in a dendritic fashion that does not resemble the pattern of a dissected plateau surface. The ‘strings’ appear to have a branching pattern, like the dendritic pattern of a simple river system. On this basis, Ollier and Sheth (2008) suggested that these mesas represent an inverted palaeo-river valley system. They further suggested that the ferricretes never formed a continuous blanket but were formed in a palaeo-river system, with interfluves of the basalts. Subsequent erosion and relief inversion produced the present landscape. In this scenario, the duricrusts no longer marks the original top of the Deccan basalt pile, but the duricrusted floor of a palaeo-river, named by the authors as the Bamnoli palaeo-river (Ollier and Sheth, 2008).

It is proposed to observe various stages of plateau consumption along the cliff margins over the main Panchgani Tableland. Some of the pseudo-karstic forms, like the large shallow depressions filled with wind-blown sediments, and with overhangs (alcoves), as well as the caves and natural bridges will also be visited.
Day 3: 01/11/2017
Field visit to Mahabaleshwar Plateau (125 km) and back
Stay at Mahabaleshwar.

Mahabaleshwar area is one of the best-studied areas in the Deccan Trap region, especially for flow-by-flow chemical stratigraphy of more than 2000 m thick lava flows (Subbarao, et al., 2000). The volcanic pile in the area belongs to the Wai Sub-group. The flows are dominated by simple flows and are characterized by multiple reddish weathered layers, known as the red boles.

Large, dissected laterite-capped mesas characterize the plateau. Geochemical fingerprinting of the Mahabaleshwar and Panchgani laterites and other laterites capping the adjacent isolated mesas strongly suggest that the laterites have developed on the topmost sequence of the Wai sub-group (Subbarao et al., 2000). This also implies that the laterites might have developed over the lava surface immediately after the end of the Deccan Trap volcanic activity during late Cretaceous-Early Tertiary times (Widdowson and Cox, 1996). Palaeo-magnetic ages on these laterites (Schmidt et al., 1983) also support this inference.

Stop 3: Wilson Point (1 km from Mahabaleshwar Town)
Wilson Point (1438 m above msl) is the highest point in southwest Deccan. It provides an excellent view of the Mahabaleshwar Plateau, one of the few high-plateaus perched on the Sahyadri (Western Ghats). The average monsoon rainfall in the area is about 6000 mm.

The octopus-shaped plateau, with an elevation of 1220 to 1430 m above msl, occurs at the highest elevation in the southern Deccan Trap region (Kale, 2000), and has patches of thick indurated laterites. The largest patch is observed at Wilson Point where the elevation rises to 1400 m above msl. Elsewhere the plateau reveals stripped surfaces (Dikshit and Wirthmann, 1992), underlain by weathered basalt. Unlike the Panchgani laterites, the laterites in Mahabaleshwar do not form mesas or tablelands because the area surrounding the laterite patches has not been deeply dissected and lowered by fluvial erosion (Kale, 2000).

The Mahabaleshwar Plateau has a radial drainage pattern. In the north, the wide, box-shaped Krishna Valley, drained by misfit Krishna River, borders the plateau. The southwestward draining Venna River originates on the plateau and crosses the Lingmala Falls (40 m) before descending down into a narrow v-shaped valley. Other rivers, like the Koyna and the Solshi, rise on the margins of the plateau and flow in a southeasterly direction. The Koyna valley marks the western limit of the plateau. A major fort, the Pratapgarh Fort, is located on an outlier on the western divide of the
Koyna valley and overlooks the coastal lowland of Konkan. River Savitri takes off from an area close to Arthur’s Seat and flows westward to the Arabian Sea.

The octopus-like shape of the plateau suggests that it has undergone extensive dissection by headward erosion of the rivers and broadening of the valleys. The tentacle-like ridges are narrow, with elongated spurs or interfluves between the river valleys.

Table 1 shows the chemical composition of the Mahabaleshwar basalts, red boles and laterites at Wilson Point. It reveals a higher concentration of the major elements, such as Fe and Al, and concomitant decrease in silica. The data also indicates a depletion of mobile elements like Ca, Na, Mg, K, Sr, etc.

Patches of laterites also occur to the north of Krishna valley, more or less at the same elevation. This concordance suggests that the Mahabaleshwar Plateau surface with a thick laterite cover was originally much more extensive, and has been subsequently dissected by stream erosion from all the sides. It represents a post-eruptive palaeo-surface that certainly extended beyond Panchgani. The present valleys of the Krishna, the Venna, the Koyna and the Solshi are younger than the laterites as well as the laterised surface that formed on the top of the Mahabaleshwar Plateau.
### Table 1: Chemical composition of the Mahabaleshwar basalts, laterites and red boles

<table>
<thead>
<tr>
<th>Element (wt %)</th>
<th>Basalts</th>
<th>MAP 059/ MAP 060</th>
<th>Red boles</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>45.9-50.6</td>
<td>30.83 /19.55</td>
<td>43.86</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>13.0-15.22</td>
<td>27.1 /16.02</td>
<td>12.70</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.04-3.02</td>
<td>4.493 /1.27</td>
<td>1.97</td>
</tr>
<tr>
<td>FeO / Fe₂O₃</td>
<td>4.23-8.24</td>
<td>27.81 /58.44</td>
<td>15.11</td>
</tr>
<tr>
<td>MnO</td>
<td>0.09-0.3</td>
<td>0.226 /0.02</td>
<td>0.15</td>
</tr>
<tr>
<td>CaO</td>
<td>8.3-10.6</td>
<td>0.34 /0.28</td>
<td>4.57</td>
</tr>
<tr>
<td>MgO</td>
<td>4.65-6.74</td>
<td>1.05 /0.72</td>
<td>4.18</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.14-0.81</td>
<td>0.15 /0.02</td>
<td>0.45</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.97-3.58</td>
<td>0.29 /0.27</td>
<td>0.33</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.08-0.41</td>
<td>0.235 /0.139</td>
<td>0.13</td>
</tr>
<tr>
<td>Ni</td>
<td>74-138</td>
<td>252 /15</td>
<td>86</td>
</tr>
<tr>
<td>Cr</td>
<td>–</td>
<td>390 /4063</td>
<td>96</td>
</tr>
<tr>
<td>Sc</td>
<td>–</td>
<td>47 /45</td>
<td>26</td>
</tr>
<tr>
<td>V</td>
<td>–</td>
<td>724 /458</td>
<td>231</td>
</tr>
<tr>
<td>Ba</td>
<td>58-148</td>
<td>728 /27</td>
<td>79</td>
</tr>
<tr>
<td>Rb</td>
<td>3-37</td>
<td>8 /0</td>
<td>14</td>
</tr>
<tr>
<td>Sr</td>
<td>158-242</td>
<td>23 /6</td>
<td>60</td>
</tr>
<tr>
<td>Zr</td>
<td>87-235</td>
<td>247/101</td>
<td>191</td>
</tr>
<tr>
<td>Y</td>
<td>27-48</td>
<td>59 /12</td>
<td>41</td>
</tr>
<tr>
<td>Nb</td>
<td>4-21</td>
<td>25 /9</td>
<td>14</td>
</tr>
<tr>
<td>Ga</td>
<td>–</td>
<td>49 /30</td>
<td>–</td>
</tr>
<tr>
<td>Cu</td>
<td>91-254</td>
<td>446 /290</td>
<td>339</td>
</tr>
<tr>
<td>Zn</td>
<td>17-111</td>
<td>215 /92</td>
<td>81</td>
</tr>
</tbody>
</table>

**Stop 4: Arthur’s Seat on the Western Ghat Escarpment (12 km from Mahabaleshwar)**

At Arthur’s Seat, the western edge of the Mahabaleshwer Plateau is delineated by the Great Escarpment of the Western Ghats. At places the scarp has a sheer drop of several hundred meters to about a km, and is embayed. The sinuous nature of the scrap, the deeply entrenched valley heads, the elongated offshoots towards the west and the occurrence of the beheaded valley of the Krishna River suggest that the escarpment has receded eastward from an earlier westward position (Kale, 2000). In other words, the present escarpment is an erosional feature. Most of the short and deep west-flowing streams have worked backward and have cut deeply into the Ghat escarpment, forming embayment. This has occasionally given rise to the phenomenon of river capture. One such capture has been identified to the south of Mahabaleshwar, involving a lower order tributary of the Koyna River (Anantapadmanabhan, 1972).

The eastward draining Krishna River has its source on the Western Ghat’s margin, just on the northern side of the Arthur’s Seat. The valley is much too wide for the existing catchment area and the back wall is missing. The river presumably did not start at the place where the present source appears to lie, but originated much further west. The present river seems to have lost its headwater, and thus is beheaded. The beheading is due to the recession of the Ghat scarp (Radhakrishna, 1965). Estimates using present valley width and length indicate that the beheaded section is about 15 km (Kale, 2000). Such anomalous occurrences of wide, box-shaped valleys, ‘hanging’ in the escarpment of the Western Ghats have also been observed in several other Trap rivers (Newbold, 1844).

**Origin of the Ghat Escarpment**

The origin of the Western Ghat scarp has been a matter of considerable debate for a very long time. Although Oldham (1893) thought that the present scarp was a dead-sea cliff, many other researchers believed that the Western Ghat scarp was initiated as a fault-scarp during the Paleocene (Pascoe, 1950; Powar, 1993). Numerous recent studies, on the other hand, have not been able to find any evidence of large-scale faulting in the vicinity of the present coastline and/or scarp line (Ollier and Powar, 1985; Widdowson, 1997). The most popular view now is that the present escarpment might have originated due to the retreat of a continental edge that was earlier formed by rifting during the late Cretaceous period (Subrahmaya, 1887; Radhakrishna, 1991; Widdowson and Gunnel, 1999).

Since many passive continental margins reveal similar geographic situations, several workers have recognized the importance of the existence of divide asymmetry in the initial stages to account for the subsequent geomorphic evolution and recession of
the great escarpments (Kale, 2000). Several models have been suggested to explain the evolution of continental margins with great escarpments, two of which appear to be better suited to the case of Western Ghat escarpment (Kale, 2000). These are as follows.

In the first model, the initial west-facing steep slope was created by rifting or faulting along the western margin of the Indian peninsular. Aggressive headward erosion by the westward-draining rivers caused the valley heads to cut deeply into the structural escarpment. Subsequently, the valleys coalesced by back-wasting of the valley sides and the elongated spurs were destroyed, leading to the net retreat of the escarpment.

In the second model (after Ollier, 1982) tectonic uplift (in response to isostatic adjustment) warped the pre-existing surface (lateritized). The up-warping of the lava flows created an asymmetrical divide with gentle slope to the east and steeper slope to the west. Following the law of unequal slopes, the west-facing steeper slope was eroded and dissected more vigorously by the streams than the gentler eastward slope. The rapid erosion created deep valleys and gorges. The elongated spurs and interfluves between the valleys and gorges were eventually eroded and the valleys coalesced to create the Western Ghat escarpment and the coastal plain.

Since the Ghat has been carved out of the trap flows, it is most likely that the Ghat scarp is younger than the Traps, and might have been in the process of evolution since the early Tertiary. This observation is also supported by the occurrence of early Eocene deposits offshore. However, the exact age and position of the initial scarp is unknown. Whatever the age and position, the palaeo-magnetic age of the Konkan laterites suggests that by late Tertiary the Ghat scarp had receded by several tens of km inland.

Stop 5: Pratapgarh Fort (25 km from Mahabaleshwar)
Pratapgarh Fort is situated at an elevation of 1080 m above msl, on the western divide of the Koyana River. Chhatrapati Shivaji, the great Maratha chieftain, built it in 1656. At this fort, he killed the Bijapur General Afzal Khan by embracing him with tiger claws. The fort has a large gate, double walls and steps from the main gate for entry to the Bhavani Temple.

The top of the fort provides an impressive view of the Western Ghat Escarpment, the coastal lowland (Konkan) and the Mahabaleshwar Plateau. A statue of Shivaji has been erected here.
Day 4: 02/11/2017
Mahabaleshwar to Morgaon and then to Aurangabad
Stay at Aurangabad.

Stop 6: Morgaon Alluvial Deposits (80 Km)
This site is located on a major denudational surface of about 750 m above msl in the interfluvies of the Mula-Mutha-Bhima Rivers in the north and the Nira River in the south. The site provides typical characteristics of the late Quaternary alluvium in this upland region *(Fig. 5)*. The deposits belong to the “Upper Bhima Formation” *(Kale and Rajaguru, 1987; Rajaguru et al., 1993)*.

The site is on the bank of the Karha River. The river originates in the rain-shadow zone of the Ghat and for most part of its course the river flows through a semi-arid terrain (rainfall less than 550 mm). The river is the northern tributary of the Nira River, which is the southern-most tributary of the Bhima River.

The most interesting feature of this site is the Toba Volcanic Ash *(Kale et al., 1993)*, which occurs in the Quaternary alluvial deposits and forms a marker horizon. The best exposures of the alluvium and the ash bed are seen downstream of the Morgaon-Supa Bridge, along the channel of the Karha River. Presently, the channel is incised into its own deposits. The deposits have also been extensively dissected by bank gullies.

The alluvial sequence at Morgaon consists predominantly of calcareous black fissured clays, with a number of gravel lenses (indurated or non-indurated), often overlying the ash bed. The ash is underlain by calcrete-rich reddish sandy-silts or old gravel. The deposits reflect different styles of sedimentation and indicate noteworthy changes in the hydrodynamic conditions in the past. Bedrock is exposed at a number of places along the channel. Coarse to fine grained sandstone and conglomerates predominantly occur on the left bank. Within these sediments, large-scale tabular cross-beding, horizontal parallel bedding and ripple, as well as parallel and convolute laminations are noticed, which indicate their deposition by a meandering river. A generalized section across the alluvial deposits is given in Fig 4 and the characteristics of the major sedimentary units are described in Table 2.
Table 2: Major Quaternary lithounits exposed on the bank of the Karha River at Morgaon

<table>
<thead>
<tr>
<th>Litho-unit</th>
<th>Thickness (m)</th>
<th>Dominant texture</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene flood deposits</td>
<td>0.5-1.0</td>
<td>Sandy-silt</td>
<td>Dark-brown in color, devoid of calcrete; recent over-bank deposits</td>
</tr>
<tr>
<td>Younger sandy gravels</td>
<td>0.25-1.50</td>
<td>Sand and gravel</td>
<td>Unsorted gravels, containing reworked calcrete nodules, microliths, mollusk and ostrich eggshell (dated to 26-22 ka) occur above the black fissured clays or in some cases are inter-bedded with the clays. The deposits imply a semi-arid to arid climate</td>
</tr>
<tr>
<td>Indurated gravelly sandstone/ conglomerate</td>
<td>2-4</td>
<td>Sand and gravel</td>
<td>Occurs particularly on left bank; sedimentary structures suggest meandering; U/Th date on cement is 40 ka; (OIS 3)</td>
</tr>
<tr>
<td>Black fissured clays</td>
<td>2-4</td>
<td>Silt and clay</td>
<td>Rich in calcretes; dominated by montmorillonite clay; deposits of semi-arid wetland, drained by sinuous streams; gravel lenses are present</td>
</tr>
<tr>
<td>Ash bed</td>
<td>0.2-0.5</td>
<td>Silt size</td>
<td>Light buff to creamy white; highly friable; contacts with units above and below are well defined; similar to Bori Tephra (c. 74 ka); often below fissured clays and above reddish sandy-salt/gravel</td>
</tr>
<tr>
<td>Reddish sandy-silt</td>
<td>1-2</td>
<td>Sand and silt</td>
<td>Rich in calcretes and fossil fragments; dominated by montmorillonite clays</td>
</tr>
<tr>
<td>Pre-ash gravel</td>
<td>1-2</td>
<td>Pebbly-cobbly</td>
<td>Sometimes overlain by ash bed; calcrete pebbles absent</td>
</tr>
<tr>
<td>Bouldery - Cobbly conglomerate</td>
<td>5-6</td>
<td>Cobbly-bouldery</td>
<td>Rounded boulder, cobble, gravel; about 400 m away from modern channel; thick weathering rind indicates antiquity of deposits; couplets of sand and silt at the top</td>
</tr>
</tbody>
</table>

Source: Atkinson et al. (1990), Sheilla Mishra (personal communication), Kale and Joshi, (2002).
Age of the Volcanic Ash
The Morgaon Ash is similar to the Bori Tephra, occurring on the bank of the Kukadi River which is to the northeast of Pune. Ar-Ar, K-Ar, Fission Track and TL ages of the ash from Bori range from 23 ka to more than 1 Ma (Korisettar et al., 1983; Horn et al., 1993; Mishra et al., 1995). Presently, the ash is believed to be about 74 ka old because the trace element chemistry of the Bori Tephra exactly matches with the youngest Toba Tephra (Acharyya and Basu, 1993; Westgate et al., 1998). Further, considering the thickness of the overlying sediments, the thickness of the ash unit, the C14 ages of the youngest gravels (22-25 ka) covering the top of the alluvial deposits, and the slight degree of weathering of the ash bed and weathering rinds of gravels overlying and underlying the ash bed, it appears that the tephra at Morgaon/Bori ash is not very old. The 74 ka Toba event has been identified as one of the mega-volcanic events in the geological record. Toba ash is an isochronous stratigraphic horizon, also directly correlated with the Arabian Sea and the Greenland Records. This suggests that the latest Toba event (74 ka) was most widespread and is clearly identifiable in the marine and terrestrial records. This, along with the simple sedimentological fact that most recent alluvial records and ash deposits are likely to be ubiquitous and best preserved, suggests that Morgaon/Bori Ash is Younger Toba Tuff, deposited at about 74 ka. The ash bed is well preserved in the Quaternary deposits. Such preservation is possible only if younger sediments cover the ash deposits without any delay or break. Therefore, it appears that the ash fall was immediately followed by large influx of black clays that buried and covered the ash unit. The deposition appears to have occurred under very low energy conditions.

Deccan College (Deemed University), Pune, excavated the black fissured clays that overlie the tephra horizon at Morgaon and discovered some Acheulian artifacts. Their study indicates that the artifacts were not transported by geological agents and do not occur within the layers but on the contacts between them. The artifacts are highly weathered. The assemblage includes boulder-sized anvil stones, but even the smallest artifacts are misfit within the clays and the fine gravels they occur on. The deposition of the clays, therefore, is contemporary with the artifacts, and later than the tephra, which lead to disagreement of these workers with the 75 ka date for the tephra. Artifacts of the types recovered from Morgaon and Bori (where they also overlie the tephra) are “Early Acheulian”. These types of artifacts, wherever dated, belong to the Lower Pleistocene. Recently, an ESR date of more than 1.2 Ma has been obtained from Isampur in the Krishna-Bhima Doab (Paddayya et al., 2002) for an assemblage very similar to that at Morgaon.
Day 5: 03/11/2017  
Field visit between Aurangabad and Lonar Crater  
Stay at Aurangabad.

Stop 7: Lonar Crater (the best preserved impact crater in the basaltic terrain (385 km))
Lonar Crater is located in a small town named Lonar in Buldhana district of Maharashtra, in the central part of Deccan Traps region (Fig. 6). The origin of the Lonar Crater has been debated since the 19th Century. There are several hypotheses regarding its origin, be it as the only available evidence of a volcanic outburst, or great gaseous extraction, or even a crypto-volcanic origin with deep-seated carbonatite. But now there is enough evidence to suggest that the crater has been formed by an impact event. The impact was caused by a hyper-velocity bolide or a meteor. The relatively unaltered morphology of the crater and the identification of subsurface breccias beneath the sediments in the crater provide evidence to this argument (Bodas and Sen, 2014). This is one of the very few hyper-velocity impact craters in the world, carved out from the basaltic target rocks, and is the only crater in lava flow sequence of a Continental Flood Basalt Province (Bodas and Sen, 2014). The crater is located on the drainage divide between the Purna and the Penganga rivers. The climate is semi-arid, with an average annual rainfall of 680 mm.

The crater has a diameter of 1830 m, and is remarkably circular and bowl-shaped (Fig. 6). The depth of the crater is approximately 150 m and the rim is raised nearly 20 m above the surrounding area. The crater floor is almost flat and covers about 1200 m in diameter. Gully erosion can be seen everywhere in the interior part of the crater. Presently, it is occupied by a saline lake of about 5-7 m depth. We can also see dense vegetation carpeting the inner slope of the crater. Within the crater, centripetal drainage system can be observed.

At a distance of about one km to the north of the main Lonar Crater, there is another smaller crater of about 300 m diameter. It is called the Ambar Lake (also called the ‘Chotta Lonar’, meaning the small Lonar). Although not yet confirmed, it is believed that this crater was also formed at the same time that the main crater was formed,
possibly as a result of the impact of a smaller fragment (Fredriksson et al., 1973). The geological succession of the crater consists of three components. These are: the basaltic lava flows (target rocks), rocks formed as a result of the impact, and the unconsolidated lake sediments (Bodas and Sen, 2014). Of these, the uppermost layer of the unconsolidated clayey to silty sediments with salt encrustations can be seen on the crater floor and basaltic lava flaws.

Fall-back fragmentary breccias can be best observed along the foot tracts that join the crater floor with the rim. The ejecta blanket with fragmented breccias and suevitic breccias, formed as a result of impact, is well-exposed in the rim area of the crater and radially outside the crater for distance of more than 2 km. Lonar town is located on the ejecta blanket (Bodas and Sen, 2014).

It was thought till recently that Lonar Crater was of the same age as Meteor Crater in Arizona, USA, with an age of between 15 and 50 ka. Recent dating of the “impact melt rock” samples from the Lonar Crater by $^{40}$Ar/$^{39}$Ar technique has yielded an age of 570 ±47 ka, an age ten times older than the oldest date given by the non-isotopic methods (Jourdan et al., 2011). Dating with fission tracks and thermo-luminescence methods indicate a much younger age. According to Jourdan et al. (2011), these impact rocks have been perturbed by the post-impact processes that include alteration and wild fires that have partially erased and reset the fission tracts, or would have affected electron charge traps used in thermo-luminescence dating (Bodas and Sen, 2014).

The lake was first mentioned in the ancient scriptures such as the Skanda Purana, the Padma Purana, as well as in the Aain-i-Akbari, written during the reign of Emperor Akbar in 16th Century. The first European to visit the lake was a British officer, J.E. Alexander, in 1823. Several temples found on the periphery of the lake are known as Yadava temples and also as Hemadpanti temples (named after Hemadri Ramgaya). Numerous temples surround the lake, most of which stand in ruins today, except the temple of Daitya Sudan at the centre of the Lonar town, which was built in honour of Lord Vishnu's victory over the giant Lonasur. It is a fine example of early Hindu architecture. The other temples, found within the peripheries of the crater, are Vishnu Mandir, Wagh Mahadev, Mora Mahadev, Munglyacha Mandir and Goddess Kamalaja Devia. The area was once part of Ashoka’s empire, and then of Satavahana’s. The Chalukyas and Rastrakutas also ruled this area. During the period of the Mughals, Yadavas, Nizam and the British, trade prospered in this area.

Geological Survey of India (GSI) has enlisted Lonar Crater as a National Geological Monument. This is a major tourist destination in Maharashtra, not only for the crater but also for the ruins of the historical temples.
Day 6: 04/11/2017
Aurangabad to Ajanta Caves and back
Stay at Aurangabad.

Stop 8: Ajanta Caves, a World Heritage Site (337 Km)
The Ajanta Caves are situated in Aurangabad district of Maharashtra. They are cut into the volcanic lava of the Deccan Trap in the forest ravines of the Sahyadri Hills and are set in a beautiful sylvan surrounding (Fig. 7). These magnificent caves, containing carvings that depict the life of Buddha, are considered to be the beginning of classical Indian art. The caves have been named “Ajanta” from a nearby village whose name is also Ajanta. During a hunting expedition in 1819, an army officer in the Madras Regiment of the British Army found these caves. Since then it has become one of the most important tourist destinations in the world. The caves are famous for their murals and paintings that stand as the finest surviving examples of ancient Indian art.

The caves are cut on the side of a cliff nearly 76 m high, which rises above a meander bend of the Waghora River (Fig. 7). The valley is situated at a calm and scenic location and Buddhist monks used to retreat in these caves during the rainy seasons and pursued intellectual discourses. Today the caves are reached by a road which runs along a terrace mid-way up the cliff. Each cave was once linked by a stairway to the edge of the water, but almost all of them are now obliterated, albeit traces of some that could be noticed at some places.

There are about 30 rock-cut Buddhist cave monuments which date from the 2nd Century BCE to about 480 or 650 CE. The excavation of the caves began in the 2nd Century B.C and continued till the 6th Century A.D. The sculptures, murals and paintings belong to different periods, resulting in the difference in styles in the execution of these paintings and sculptures. The mid-5th Century A.D to mid-6th Century A.D witnessed a flurry of activities at Ajanta. A famous Chinese traveler, Hieun Tsang, visited India during the first half of the 7th Century A.D, and left a vivid and graphic description of the flourishing Buddhist establishment here.
There are in all 30 caves hewn out of rock, which also include an unfinished one. The caves display sculptures which are masterpieces of Buddhist religious art, with figures of the Buddha and depictions of the Jataka tales. Execution of the paintings began with elaborate preparation of the rock surface. Chisel marks and grooves were left on the surface of the rocks so that the layer applied over it could be held firmly. On the rough surface of walls and ceilings, a blend of ferruginous earth mixed with rock-grit or sand, vegetable fibres, paddy husk, grass and other fibrous material of organic origin was applied. Over this ground surface, a second coat was applied that consisted of mud and ferruginous earth mixed with fine rock-powder or sand and fine fibrous vegetable material. The final finish was with a thin coat of lime wash. The outlines were drawn boldly over these lime-washed surfaces and then the spaces were filled with requisite colors in different shades and tones to achieve the effect of rounded and plastic volumes. Glue was the chief binding materials used for these paintings.

The object of worship is a Stupa. In date and style, the caves can be divided into two broad groups. These are (1) a Buddhist community, comprising of five sanctuaries or Chaitya-grihas (caves 9, 10, 19, 26 and 29), and (2) a monastic complex, Sangharamas or Viharas (all the other caves). The caves were excavated during the supremacy of the Vakatakas and Guptas. Under the reign of the Gupta Dynasty, Indian art reached its peak. The earliest excavations belonged to the Hinayana phase of Buddhism. The second phase saw the introduction of new patterns in the layout, both in paintings and in sculptures. The main theme of the paintings is the depiction of various Jataka stories, different incidents associated with the life of Buddha and the contemporary events and social life. Geometrical and floral designs decorate the ceilings of these caves (Fig. 8).
The styles presented by Ajanta Caves have exerted a great influence on the art and architecture within and beyond India, extending up to Java. The Ajanta Caves indeed bear exceptional testimony to the evolution of Indian art, as well as to the determining role of the Buddhist Community, intellectual and religious foyers of the Gupta Dynasty and their immediate successors. The refined decoration, the balance of the compositions, and the marvelous beauty of the feminine figures depicted in the paintings were among the major achievements of the Gupta and post-Gupta styles and confer on them the ranking of a masterpiece of universal pictorial art (UNESCO/CLT/WHC).

Day 7: 05/11/2017
Departure from Aurangabad to New Delhi by Flight
Stay at New Delhi.


Fox, C.S. 1923. The bauxite and aluminous laterite occurrences of India. Memoir, Geological Survey of India, 49 (part I).


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Geomorphologists, Allahabad.
Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
Geomorphological Field Guide Book on Kachchh Peninsula

**Itinerary**

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KACHCHH PENINSULA: AN INTRODUCTION

Kachchh district, located at the western extreme of India, lies between 22° and 24° N latitudes and between 68° and 71° E longitudes. It is the second largest district in the country, and has an area of 45612 sq. km. The district is flanked on the south by the Arabian Sea. In the north and the east it is flanked by two vast saline marshes, the Great Rann of Kachchh (~15127 sq. km), and the Little Rann (~4000 sq. km), with few small rocky islands in between (~83 sq. km). In the west lies a vast unfinished delta with tidal creeks and thickets of mangrove (1285 sq. km; Kar, 2011). Between the Great Rann and the hilly central part lies a vast featureless saline plain with patches of halophytic grasses, which is called the Banni (~2525 sq. km). Consequently, large parts of the district are inhospitable. Most of the human habitations in Kachchh district lie especially in the central part of the district, along an elongated tract with rugged hilly terrain and flanked by shallow plains, which is called the ‘Kachchh Mainland’. The shape and the broad topographic configuration of Kachchh Mainland resemble that of a tortoise shell, which is possibly why the name ‘Kachchh’ (a Sanskrit word for tortoise) was given to this land. The district has an arid climate. Its mean annual rainfall is 348 mm, received mostly during the summer monsoon months of June to September, but with high spatio-temporal variability that commonly results in either drought or localized high-intensity rains. Mean summer temperature in May is 42°-43°C, but it often goes up to 45°-47°C. Winter is mild due to the nearness of the sea, the mean day temperature during January being 28°-30°C, while the mean minimum temperature at night falls to 7°-10°C. The structural styles, the lithological make-up and the tectonic events have played crucial roles in the geomorphological evolution of the district, as well as in shaping its present landforms. The following summary of our current understanding of the geology and geomorphology of Kachchh district may help to appreciate the landscape of the district.

Geology and Geomorphology of Kachchh

Kachchh is a western marginal peri-cratonic rift basin in India that is oriented E-W at the periphery of the Indian Craton (Biswa, 1987; Biswas et al., 1993; Fig. 2). The palaeo-rift of the Thar and the Southern Indus basin of Pakistan (Zaigham and Mallick, 2000) borders it on the north. To the south occurs another parallel rift basin, the western offshore extension of the Narmada rift, with the Saurashtra horst in between them. The N-S trending Cambay rift basin crosses the above two parallel rifts. Together, the three rifts form an intersecting rift system around the foundered cratonic block of Saurashtra at the trailing edge of the Indian continental plate. The Mumbai offshore shelf extends south of the Narmada rift along the West Coast Fault. This shelf is also rifted and is featured by the N-S trending grabens/half-grabens and horsts.
As mentioned earlier, the landscape of Kachchh Mainland is dominated by a central highland, which is surrounded by lowlands (Fig. 3 to 5). The highland has a rugged hilly terrain with sparse vegetation, exposing the Mesozoic rocks (Middle Jurassic to Early Cretaceous), bordered by thin strips of gently dipping Cenozoic rocks (Paleocene to Pleistocene and Recent), which form the coastal plains. The lowlands are extensive alluvial plains, or mud and salt flats (Rann), and grassy flats (Banni). The marginal hill ranges in the mainland, with escarpments facing the plains are sharp marginal flexures of Mesozoic rocks that are well exposed along the length of the highland.

Fig. 2. Rifted western continental margin of India and location of Kachchh Rift (KR). KR is located within intersecting rift complex in the highly tectonised northern part of the WCMI. All bordering rifts are in inversion mode. IFB: Indus Foreland Basin; NPF: Nagar Parkar Fault; NKF: North Kathiawar Fault; CR: Cambay Rift; NR: Narmada Rift; SH: Saurashtra Horst; DVP: Deccan Volcanic Province; CT: Chaman Transfer fault; ONT: Ornachnai Transfer fault; MT: Mekran Thrust; BOB: Baluchistan Orogenic Belt; OFZ: Owen Fracture Zone (Murray Ridge); RWCM: Rifted Western Continental Margin (After Biswas, 1987).

Physiographic Divisions

The Kachchh region provides excellent examples of tectonically-controlled landscapes where the landforms are the manifestations of earth movements along tectonic lineaments of the Pre-Mesozoic basin configuration that was produced by the primordial fault pattern in the Precambrian basement (Biswas, 1971, 1974). Taking into consideration the factors
of altitude, slope and ruggedness of relief, Kachchh can be divided into the following four major physiographic units from north to south: (1) the Ranns, (2) the low-lying Banni Plain, (3) the Hilly Region, and (4) the Southern Coastal Plain (Fig. 3). The Gulf of Kachchh between Kathiawar Peninsula and Kachchh Mainland, the Banni grassland between the Mainland and Pachham Island, and the Great Rann of Kachchh between the Island Belt and Nagar Parkar Ridge are the major structural lows. The Gulf of Kachchh shallows eastward, ending up as a mudflat between the Wagad and the Kathiawar highland to the east of the Mainland. This mudflat is called the Little Rann of Kachchh. A description of the four major physiographic units follows.

Fig. 3. Major physiographic divisions of Kachchh Mainland (after Biswas, 1982).

Fig. 4. SRTM DEM of Kachchh landscape. The first order topography is controlled by rift structure. Highlands, surrounded by lowlands, suggest horst and graben features. NHR: Northern Hill Range; KHR: Katrol Hill Range; SWH: South Wagad Hills; KDHR: Kaladungar Hill Range; GDHR: Goradongar Hill Range.
(1) **The Ranns:** The Ranns are the most remarkable and unique features of Kachchh, having a flat terrain hardly beyond 3-4 m asl. The Great Rann of Kachchh occurs in the north of the district, while the Little Rann is in the east. As stated earlier, a chain of islands occur within the Great Rann (Fig. 5). The Ranns mostly remain dry, except during the rainy season when it is covered by water. During the dry summer and winter months, much of the Rann surface is covered with salt encrustation. Merh and Patel (1988) identified the following five geomorphic units in the Ranns (Fig. 5). These are: (a) Bet Zone (BTZ), (b) Linear Trench Zone (LTZ), (c) Great Barren Zone (GBZ), and (d) Little Rann of Kachchh (LRK).

(2) **The Banni Plain:** The plain of Banni represents an embayment between the Kachchh mainland in the south, the uplifts of Pachham in the north, and the Wagad uplifts in the east and covers the area ~ 6000 sq km (Fig. 4 and 6). It rises little higher than the surrounding Rann and is covered with green grass and other shrubs. No outcrop is seen within these featureless plains. It receives water from the Mainland and the islands from the north and east respectively during rainy seasons.

(3) **The Hilly Region:** The hilly areas within the district occur as ‘Uplifts’, and can be broadly divided into the following three groups: (a) the Island Belt Uplift, (b) the Kachchh Mainland Uplift, and (c) the Wagad Uplift. The Island Belt Uplift consists of four highlands: the Pachham, the Khadir, the Bela and the Chorar highlands, which occur as islands (Bets) within the Great Rann of Kachchh in the north, and form an E-W chain of uplifts. In fact, these four highlands were islands during the Late Tertiary-Quaternary period when the Great Rann was inundated by the sea (Biswas, 1971). The Kachchh
Mainland Uplift occurs in the west, and the Wagad Uplift in the east (Fig. 4 and 6). The Mesozoic (Middle to Upper Jurassic) rocks are exposed in the highlands, bordered by the Tertiary and Quaternary rocks in the southern and western peripheral plains. Early Cretaceous rocks are present only along the southern slopes of the Kachchh Mainland Uplift, overlain by the Deccan Trap volcanic flows, and eastward by the on-lapping Tertiary strata (Fig. 7).

(a) **The Island Belt Uplift** (IBU) comprises of four south-tilted blocks from west to east: the Pachham Uplift (PU), the Khadir Uplift (KU), the Bela Uplift (BU) and the Chorar Uplift (CU; Fig. 4 and 6). The northern boundary of all the Islands is steeper while the gradient is very low towards south.

The Pachham Uplift (PU) is located north of Kachchh Mainland Uplift across the Banni Plain (Fig. 6). The uplift is a NW-SE oriented quadrangular block with southward tilt. It is surrounded in the N and W by mudflats of the Great Rann of Kachchh and in S by the Banni Plain. To the east, a 22 km stretch of Great Rann separates PU from KU. PU is faulted in the middle, forming two parallel south-tilted fault blocks: the Kaladongar Hill in the north and the Goradongar Hill in the south, with a central valley in between, which is covered by alluvium. The central valley, the Dhorawar-Tuganipur syncline, is created by downthrow of the Kaladongar block against the Goradongar Fault (GDF). Like other uplifts, the hill ranges here are deformation zones. The northern margin fault (Island Belt Fault; IBF) is inferred from the sharp edge of the block and truncated marginal anticlines. The southern Goradongar Fault (GDF) is well exposed. It strikes NW-SE, parallel to the inferred IBF. It is a second-order reverse fault associated with rift inversion.

![Fig. 7. Geological map of Kachchh (after Biswas and Deshpande, 1970).](image)

The Khadir Uplift (KU) is located to the NE of Kachchh Mainland Uplift across the Banni Plain (Fig. 6). The structure of KU is the simplest of all the uplifts. It is a simple
triangular block, sloping down to the south without any marginal folding. The steep northern escarpment is the maximum elevated part of the uplift. The back-slope dips gently (3-5°) to the south. Radial dip pattern on the back-slope suggests a large half-dome structure. This is also indicated by the gently curved southwestern outline of the uplift, cut off by the escarpment on the north. The straight northern escarpment also suggests that it is a receding scarp of the hidden IBF. The outcrop of boulder conglomerates at the foot of the scarp at Cheriya Bet in the north-central part shows apparent reversal of dip. KU back-slope is affected by few small-scale faults, most of which are accompanied by basic dykes. The southern tip of this triangular uplift is bordered by the Kakindia Fault (KF), which continues eastward across a narrow stretch of mudflat from NW-SE to E-W, with a curved trend, and connects with Gedi Fault (GF) between the Wagad Uplift (WU) and the Bela Uplift (BU; Fig. 6). A series of domes occur along this belt. These are, from west to east, the Kakindia Bet, the Kara Bir, the Gora Bir and the Gangta Bet. Apparently, KF is the extension of the GF and the structures are related to Desalpur Deformation Zone (DDZ).

The Bela Uplift (BU) occurs to the north of Wagad Uplift (WU), juxtaposed by Gedi Fault (GF). This uplift is a horst block between the Great Rann Graben (GRG) in the north and the Rapar Half-Graben (RHG) in the south, bound by IBF and GF, respectively. The faulted edges are tilted opposite to each other, forming a central synclinal low, the Balasar Low. The bounding faults are accompanied by deformation zones with chains of folds of varying types and dimensions as seen in all other upifts. The uplift has three structural zones: (a) The Bela Flexure Zone (BFZ) along the northern margin, (b) the Central Balasar Low (CBL), and (c) the Desalpur Deformation Zone (DDZ) (Fig. 6). BFZ is associated with IBF and DDZ with GF. The tilted edges of the horst with a central low suggest a possible faulting in the middle at the basement level between two oppositely tilted blocks. Bela flexure is a narrow, stretched and elongated anticline. At the eastern end occurs a large dome, Mouana dome, with swarms of basic dykes at the core suggesting presence of a laccolith at depth. Low amplitude faults accompanied by basic dykes are common as in other uplifts.

The Chorar Uplift (CU) is the smallest uplift in the IBU, located at the northeastern corner of Kachchh rift basin (Fig. 6). It is oriented NE-SW as the strike of IBF swings from E-W to NE-SW. It is a domical uplift of very low relief, mostly covered by Tertiary rocks, excepting the elevated and eroded central part. The straight northwestern margin with steeper dips of beds and convex southwestern periphery with radial dips suggest the same structural geometry as in the other uplifts. Due to low amplitude of fading IBF, the fault flexure shows only steep dips and no deformation zone as in the other uplifts.

(b) The Kachchh Mainland Uplift (KMU) is the largest uplift in the Kachchh Rift basin. It is a broad-topped oblong upwarp, which is elongated E-W along the Kachchh
Mainland Fault (KMF) in its north. On either sides of the Median High, this uplift plunges towards the Arabian Sea Shelf in the west (Lakhpat and Narayan Sarovar noses) and towards the Little Rann in the east (the Bhachau and the Anjar noses) (Fig. 6 and 8). It is a south-tilted block along the KMF. The E-W strike of KMF curves westward into a WNW-ESE strike, making a concave trend of the northern faulted margin. The back-slope of the uplift slopes gently southward from the Northern Deformation Zone (NRDZ) along the KMF. The slope is featured by small second-order faults and associated folds. The back-slope is faulted in the middle by a major E-W striking Katrol Hill Fault (KHF), which divides the uplift into two south-tilted blocks repeating the stratigraphic sequence.

(c) The Wagad Uplift (WU) along the SWF, is located in the eastern part of the Banni Half Graben (BHG), and is the second largest uplift in the basin (Fig. 6). It is an E-W oriented large domical uplift, bound by faults with a central dome and broad peripheral noses, the Chobari Nose (CN) in the west and the Adesar Nose (AN) in the east. This uplift is placed en echelon with respect to KMU, northeast of the eastern plunge of the Bhachau anticlinal Nose (BN). WU is tilted down to the north along the GF. The up-tilted southern edge along the South Wagad Fault (SWF) is a complicated fault zone associated with a complex of faults and folds.

![Tectonic map of Kachchh](image-url)
(4) **The Southern Coastal Plain**: This plain borders the Kachchh Mainland, overlooking the Gulf of Kachchh in the south and the Arabian Sea in the west (Fig. 3 and 4). The coastline has been broadly divided into five segments based on geomorphologic variations (Kar, 1993). These are: (a) the deltaic coast to the west of Kori Creek, (b) the irregular drowned prograded coast between Kori Creek and Jakhau, (c) the straightened coast between Jakhau and Bhada, (d) the spits and cuspate foreland complex between Bhada-Mandvi and Mundra, and (e) the wide mudflat coast to the east of Mundra up to the Little Rann.

**Regional Geology of Kachchh**

The Kachchh basin preserves about 2000 to 3000 m thickness of Mesozoic sediments and about 1000 m thickness of Cenozoic sediments (Biswa, 1977, 1982). The Tertiary rocks are exposed along the coastal belt of southern and western Kachchh, bordering the Mesozoic rocks (Fig. 7). The Quaternary sediments consist of a wide variety of sediments, ranging from marine to fluvial, laccustrine and aeolian deposits. In the coastal plains the late Quaternary deposits mostly consist of alluvium and calcreted or ferricreted loose sediments, covering the older deposits. The exposed Tertiary sediments are mostly littoral to shallow marine shelf sediments, deposited in the peripheral and intervening structural lows that border the Mesozoic uplift areas.

**Mesozoic Stratigraphy**: The Mesozoic rocks of Kachchh were first mapped by Wynne (1872), who classified the sequence into the upper and the lower Jurassic groups. Waagen (1875) proposed the popular four-fold subdivisions, namely, the Pachham, the Chari, the Katrol and the Umia Series. Rajnath (1942) restricted the term ‘Umia’ only to the lower Umia of Waggen. The upper Umia, made up of non-marine beds with plant fossils, was called by him as Bhuj Series of Middle Cretaceous, or of even slightly younger age. Biswas (1977) recognized three main lithologic provinces within the basin. He classified the rocks of each province separately and named the units according to their strato-types (Biswas, 1977). The litho-stratigraphic sequence of the mainland is divided into four formations, named as the Jhurio (Jhura), Jumara, Jhuran and Bhuj formations (Biswas, 1977, 1981). The major lithological characteristics of these formations worked out by Biswas (1974, 1977, 1982 and 1987) are briefly described below.

**Jhurio Formation** is a thick sequence of limestone and shales with bands of ‘golden oolites’. The type section occurs in Jhurio hill, in the north-central Mainland. The upper part of the formation is made up of thinly-bedded white to cream coloured limestones (pelmicrite and bimicrite), with thin bands of ‘golden oolite’ (Balgopal, 1973). The middle part is composed of thick beds of grey-yellow weathered shales, alternated with thick beds of golden oolitic limestones. The lower part comprises of thin beds of yellow and grey limestone (Agarwal, 1957; Balgopal, 1973). The physical and biological aspects
of the formation indicates littoral to infra-littoral environment. The formation ranges from Bathonian to lower Callovian.

**Jumara Formation** is thick argillaceous, conformably overlying the Jhurio Formation. It has been named after its type section in Jumara hill to the north of Jumara village and near the Great Rann. The formation is characterized by monotonous olive-grey gypseous laminated shales with thin red ferrigenous bands. The ~300 m thickness of the formation is uniform throughout the area. Local disconformity is observed at places where the Jhuran shales are seen resting over the eroded Dhsa oolite member. The Jumara formation ranges age between Callovian and Oxfordian.

**Jhuran Formation** comprises of a thick sequence of alternating beds of sandstones and shales. It is divided into four members, the lower, the middle (Rudramata shale), the upper and the Katesar (Biswas, 1977). The lower member consists of alternating red and yellow sandstone and shale. The middle member is mostly shale, comprising of dark grey to black laminated gypseous shales. The upper member is predominantly arenaceous and is composed of red and yellow massive current-bedded sandstones with intercalations of shale, siltstone and calcareous sandstone. Kimmeridgian to Valanginian age is fixed for this formation.

**Bhuj Formation** is named after its type locality around Bhuj. This formation is characterized by a huge thickness of non-marine sandstones of uniform character. These rocks occupy about 3/4th of the total area of the Mesozoic outcrop in Mainland Kachchh. The lower member is characterized by cyclic repetition of ferruginous or lateritic bands, shale and sandstones. The upper member consists of whitish to pale brown, massive, current-bedded, coarse-grained, well-sorted sandstones. The formation is bounded by the plains of disconformity. In the south, Deccan Trap rests on the eroded undulating surface of this formation. The sediments represent deltaic deposits with distal part of the large Cretaceous delta front towards the west and the proximal part (fluvial) to the east in the direction of the land. Lower Cretaceous (Valanginian to Santonian) time range is fixed for this formation.

**The Deccan Trap** forms a more or less linear outcrop, extending across the Mainland with a maximum width of about 10 km in the east near the town of Anjar, and gradually tapering westward. Lava flows are dominantly tholeiitic basalts, occupying the southern and southwestern slopes of the central highland. The trappean flows show gentle southerly dips and are believed to be of *pa hoe hoe* type (Biswas and Deshpande, 1973). Six major flows have been reported at the eastern extremity (Dhola Hills near Anjar), where they show alternations of columnar and amygdaloidal basalts, occasionally separated by inter-trappean beds. Associated with the trappean flows are a number of long, narrow dykes that occur to the N, NW and NE of the lava flow. Most of the dykes
occur along transverse faults, extending N-S, NNE-SSW and NW-SSE. An interesting aspect of the Deccan volcanism in Kachchh is the occurrence of alkaline basalt and its derivatives as plugs, laccoliths and sills within the dome structures in the Mesozoic rocks. The inter-trappeans were deposited in shallow basins and depressions over trappean surfaces, fed by simultaneously formed rivulets. An uppermost Cretaceous age (Maastrichian) is inferred for these inter-trappeans. Laterites form a narrow elongate Paleocene belt, a few hundred meters wide and several hundred kilometers long, sandwiched between the basalts of the Deccan Trap and the Tertiaries, and forms a terrain that is characterized by 10 to 15 m high elongated ridges, separated by broad intermittent valleys.

**Tertiary Stratigraphy:** Wynne and Fedden (1872) studied these rocks for the first time. Biswas (1974) proposed a revised stratigraphy and established that the Tertiary sediments in Kachchh were deposited on the eroded surface of the Deccan Trap and the Mesozoic sedimentaries. Deposition started with a marine transgression during Lower Eocene and ended in Pliocene. During Paleogene, deposition was restricted to the western part of the Kachchh Mainland, the thickest parts being exposed in the southwestern coastal plain which was the deepest part of the basin. The following is a brief summary of the Tertiary formations as described by Biswas (1974).

**Madh Series:** The type area of the rocks of this series is the well known village of Mata-no-Madh in western Kachchh. It consists of volcanoclastic sediments deposited in variable environments, ranging from fluvial to littoral (Biswas, 1974).

**Berwali Series:** The series is divisible into two stages, the lower consisting of gypseous and ochreous clays and marl containing several varieties of mollusks and foraminifers, and is seen in Kakdi Nadi section (Kakdi Stage), and the upper stage is well exposed in Babia hill in western Kachchh comprising a fossiliferous fragmental limestone with a basal calcareous clay bed (Babia Stage).

**Bermati Series:** This series forms a well exposed continuous belt south of Lakhpat in northwestern Kachchh. It is divisible into two stages; the lower Ramania stage consists of greenish-grey marl and argillaceous limestone with a basal boundary clayey marl bed deposited in an epineritic environment of a slowly regressive sea (Biswas, 1974).

**Khari Series:** This series overlies unconformably the Bermoti series and is well exposed in the clifffy banks of the Khari River in southwestern Kachchh. The Khari series is made up of two distinct stages distinguishable. The lower Aida stage is composed of variegated siltstone, the lower 16 m of which is barren, but the upper part contains Lower Burdigalian fossil assemblage. The upper part of the series, the Vinjhvan Stage consists of grey to khaki-coloured gypseous clay with hard marl bands packed with fossils. This stage forms the main bulk of the Lower Miocene of Kachchh. The clays of this stage
contain a rich assemblage of Upper Burdingalian fossils. As the Khari series is seen overlapping the Deccan Trap directly, it suggests that this marine transgression was the most powerful one in the history of the Tertiary sedimentation in Kachchh.

**Kankawati Series:** Well exposed around Kankawati River between Sandhan and Vinjhan, this series consists of grey micaceous and calcareous sandstone, lenticular bands of conglomerate and Khaki grey clay. The upper part is mainly pinkish hard calcareous grit and conglomerate containing abundant foraminifers. This series has been tentatively assigned a Pliocene age and has been correlated with the Manchhar Series of Sindh-Baluchistan.

**Regional Structures of Kachchh**

The structure of KR is designed by six major E-W striking intra-rift faults: KMF, KHF, SWF, GF, GDF and IBF, and two rift bounding faults: NPF and NKF, respectively on the north and south (Fig. 8). The basement blocks and the bounding faults are not exposed (Fig. 9). The surface locations of the faults are inferred from the geometry of the marginal flexures which are affected by a zone of parallel late-generation faults. These faults are interpreted to be the upward extension of sub-vertical basement faults which affected the Tertiary strata of the adjacent half-graben (Fig. 9). The common geometry seen in all the uplifts is knee and ankle-bend fold with a short, near-vertical faulted forelimb and a gently dipping, long-back limb. This geometry suggests draping of the ductile sediment layer over the faulted edge of a hard, brittle and tilted basement block. It is assumed that the steep escarpment face and the axis of the knee-bend fold mark the approximate location of the sub-vertical basement fault hidden below the folded sediment layer. This layer is affected by upward propagating faults from the main basement fault. This is confirmed by shearing of the forelimb and juxtaposition of steeply upturned Tertiary strata against the sheared Mesozoic strata of the fore-limb. A zone of parallel, closely-placed sympathetic faults exposed along the foot of the fore-limb scarp helps in tracing the master fault. Following this criteria, the approximate locations of the above mentioned major faults were traced on a map.

![Fig. 9. N-S section across Kachchh, showing fault locations and their subsurface configuration.](image-url)
**Primary Faults**

**Nagar Parkar Fault (NPF):** This fault marks the northern boundary of the rift basin. It is defined by the boundary between basement and rift sediment. However, this fault is not well exposed. The fault is drawn along a prominent geomorphic high, Allah Bandh, in the western part of GRG and the basement outcrop at Meruda Takkar monadnock (Biswa and Deshpande, 1968) in E-W direction (Fig. 7). The Allah Bandh is a ridge of Holocene sediment uplifted during 1819 earthquake. Basement outcrop at Kalinjhar Hill in Nagar Parkar, Pakistan, 60 km NW of Meruda hill confirms that north of the traced fault is a Precambrian terrain. This interpreted location of NPF is further supported by the sharp boundary between the mud flat of Great Rann of Kachchh and the dunes of Thar Desert. This geomorphic boundary is a receded fault line scarp. Outcrop of granite boulder conglomerate in Cheriyabet, north of KU, suggests presence of piedmont conglomerate fan deposit in the narrow graben between the traced fault and IBF. This confirms the traced location of the fault. As discussed earlier NPF is an important transfer fault between rift and foreland basin. It continues eastward across the Cambay basin as Tharad fault along a transverse ridge in line with the Kalinjhar hill of Nagarparkar.

**North Kathiawar Fault (NKF):** This fault is not exposed. It is postulated approximately along the northern straight edge of the SH mainly on the basis of geomorphology. This southern margin of Gulf of Kachchh is the elevated plateau of Saurashtra which is bound by proven faults in all other sides. The gulf (GOKHG) deepens progressively southwards attaining maximum depth near the plateau. This suggests uplift of the plateau as a horst block against the half-graben. This is supported by the gravity data. It is presumed that the fault is passing offshore along the northern edge of SH. Due to lack of offshore data the fault could not be confirmed. However, progressive thickening of KR sediments in GOKHG towards south and repetition of Lower Cretaceous and Deccan Trap formations are definite indication of the presence of a fault (Fig. 6). On the map approximate location of the fault is shown between Gulf of Kachchh and Saurashtra (Kathiawar) plateau.

**Kachchh Mainland Fault (KMF):** KMF is the biggest and longest fault in the region and the principal zone of weakness. It extends for 200 km along the northern edge of Kachchh Mainland Uplift (KMU). The fault has a prominent geomorphic expression. The lofty hills of the northern range appear to rise abruptly from the Banni plain, which is the downthrown side.

**South Wagad Fault (SWF):** The southern part of Wagad uplift is much faulted and appear to have been shattered and broken into several blocks wedges bounded by faults. These faults have been collectively called South Wagad Fault System. The southern edge of the Wagad uplift is tilted up along this system of faults.
**Island Belt Fault (IBF):** IBF is not well exposed along the island chain of uplifts, and is concealed under the Rann sediments. The faulting is indicated by steeply-dipping beds of the forelimbs of the drape – folds and the imposing escarpments facing north. At the foot of the northern scarp of Pachham (Kaladongar hills), hard sandstone beds dipping 60°-80° to the north into the Rann sediments indicate the fault. High and erratic dips along the margin of the uplifts bordering Rann indicate faults. The fault appears to have been dislocated by left lateral NE-SW strike-slip faults, which separated Island Belt Uplift (IBU) into four discrete blocks [Pachham Uplift (PU), Khadir Uplift (KU), Bela Uplift (BU), and Chorar Uplift (CU)]. These blocks were rotated anticlockwise and shifted progressively westward as indicated by their axial orientation (Fig. 6).

**Secondary Faults**

**Katrol Hill Fault (KHF):** KHF and GDF are the post-depositional later generation faults within the uplifts KMU and PU, respectively. KHF strikes parallel to KMF. To the west it splays out into two faults, one continues to the west in the same strike and the other strikes NW as Vigodi fault and its splay outs – Vigodi – Gugriana – Khirasra – Netra faults (VGKF) (Fig. 6 and 8). The later faults meet the KMF near Lakhpat. The west-striking KHF is dislocated and shifted southward by NE-SW Jarjok fault.

**Goradongar Fault (GDF):** This Fault brings up the southern part of PU (Goradongar Hills). It is a sub-vertical fault with changing dips as noted in other cases. The associated conjugate fault system and folds are typical of a strike-slip fault. The marginal flexures and oblique folds related to subsidiary faults present a complicated fault and fold pattern of the Goradongar uplift. The Gedi Fault (GF) between Bela horst and Rapar half-graben is in the same alignment as the GDF across the Banni low covered by recent sediments.

**Banni Fault:** BHG is the south-sloping hanging wall of IBU block with a central arch where MH crosses it. On this arch in the middle of the basin a WNW-ESE striking fault, parallel to IBF, had been mapped by 2D seismic survey (ONGC source). This fault referred to as Banni Fault, is not exposed.

**Gedi Fault (GF):** The fault separates Bela Horst (BU) and north tilted Wagad block. RHG, sloping north, is the backslope of WU against it (Fig. 6 and 8). GF strikes E-W with upthrow of BU on the north. It shows the same characteristics as seen in other master faults. GF is seen to extend into Gangta uplift. The E-W chain of faulted Karabir, Gorabir and Gangta anticlines in the same alignment as discrete uplifts suggests westward extension of GF. Evidently, it appears that GDF and GF are parts of the same fault.

**Transverse Faults**

The northern range of the Mainland is affected by innumerable small-scale faults which cut across the flexure irrespective of the individual folds. Several of them form
boundaries between adjacent domes or anticlines. In west these faults strike NE-SW separates differently uplifted domes. In central Mainland innumerable small scale faults bunch together to form a wide zone of small scales faults trending NNE-SSW across the Mainland from the Mainland fault in the north to Katrol Hill fault in the south. Faults in almost every direction are noted within this zone. The faults striking NE-SW to NNE-SSW (20°-200° to 40°-220°) are predominant. The eastern and western limits of the domes are marked by N-S transverse faults. The N-S and NW-SE fractures are occupied by basic igneous dykes. The steep scarp marking the KHF is a prominent geomorphic feature of the area. All along the base of the fault scarp, several dissected colluvial fans are encountered (Thakkar et al. 1999). The NNE-SSW, NE-SW, NW-SE and NNW-SSE trending faults exhibit younger fault scarp morphology. This is evident by little or no colluvial deposits along these scarps and absence of gullies or projecting spurs. Moreover, these faults are continuous and never found to cut across by other faults unlike the KHF, which is divisible into several segments by transverse faults cutting across it. The lateral movement along these faults is very conspicuous in the field. Effects of these faults are seen in the form of horizontal shifting of rocks and the E-W trending faults including the Katrol Hill Fault and Kachchh Mainland Fault. The N-S and NW-SE fractures are occupied by basic igneous dykes. The number of transverse faults is greater to the south of Katrol Hill Fault than in the north.

Median High

The most striking feature of the Kachchh basin is the occurrence of a meridianal high in the middle of the basin. This high therefore is called the Median High or Ridge. It has influenced the sedimentation thickness of the Mesozoics. This high passes transversely across both positive and negative element. Structures along this high expose the oldest sediment. They are situated at the highest structural level and show greatest amplitude of the uplift (Fig. 8).

Igneous Activity

Mesozoic sediments are affected by intensive igneous activities. Igneous intrusions are fairly common in all the uplift areas, both in major and minor uplifts. All known forms of intrusive bodies are present and are mainly concentrated in the narrow deformation zones accompanying the master faults. The intrusive bodies are associated with folds and faults as dykes, sills, laccoliths and plugs. The maximum intensity of igneous activity is seen in the northwestern part of Kachchh Mainland Uplift west of Median High and in the northern part of PU (Kaladungar Hill) along the marginal faults, i.e., KMF & IBF. A series of igneous plugs occur along an E-W belt in the central region of KMU, sub-parallel to the rift axis and close to the Katrol Hill Uplift. Some of these plugs are connected to the
outliers of Deccan Trap flows capping the hills. Evidently these plugs are the main feeders of Deccan Trap flows, now exposed by erosion. The main Trap province of Kachchh is about 10-20 km to the south, bordering the coastal plain. The Trap flows drape over the tilted eroded surfaces of the Mesozoic rocks and dip parallel to the overlying Tertiary beds. The plugs consist of alkaline basalts with xenoliths of spinel, lherzolite (Karmalkar, et al., 2002) and olivine nodules (De, 1964) indicating that they are derived from upper Sub-Crustal Lithospheric Mantle (SCLM) at a depth of ~40 km. The intrusive bodies occurring as laccoliths, master dykes, massive and extensive discordant plutonic bodies, large sills as well as smaller dykes & sills associated with marginal deformation zone in the western KMU are composed of gabbroic rocks. The massive plugs and dyke swarms at the core of the bordering Kaladongar anticline and large sills associated with the folds in the eastern part of the Goradongar flexure of Pachham Uplift are picrites associated with lamprophyre and diorite. The Trap flows are predominantly tholeiitic basalt. The associations of different groups of mafic and ultramafic rocks are suggestive of different phases of igneous activity viz. synrift stage, postrift thermo-tectonic stage and inversion stage. During the earlier rift stage mantle derived ultramafic rocks might have sheared the lithosphere by discontinuous stretching. During the later stage the plume (Reunion) related Deccan Trap extrusion took place.

**Seismicity of Kachchh**

Kachchh lies in the highest zone of seismicity in India (Zone V) and has experienced several large and moderate seismic events during the historical times. The 2001 Bhuj Earthquake ($M_w = 7.7$) was the most devastating earthquake of recent time, which claimed 20,000 lives. Prior to this earthquake two other large events, i.e., the 1819 Allah Bund Earthquake ($M_w = 7.8$) and the 1956 Anjar Earthquake ($M_w = 6.0$) were recorded. It is suggested that owing to its intra-plate setting, the 2001 Bhuj event was an analog of the New Madrid Earthquake of eastern USA (Boudin et al., 2001; Tuttle et al., 2001). Several studies have reported fault plane solution for the 2001 Bhuj Earthquake and the 1956 Anjar Earthquake, which suggest that these took place on south-dipping reverse fault (Chung and Gao, 1995; Negishi et al., 2001). It has also been reported that after the 2001 Bhuj Earthquake, Gujarat region has experienced enhanced seismic activity (Rastogi et al., 2012).

**Quaternary Sediments**

There are three principal areas in Kachchh, which have witnessed significant Quaternary sedimentation. One is the flat saline Ranns, i.e., the Great Rann of Kachchh and the Little Rann. These flat terrains made up of silt and clay, rich in salt, and occasional sand bodies
with no surface exposures of any hard rocks, are the products of marine deposition (Platt, 1962; Biswas, 1974; Glennie and Evans, 1976; Roy and Merh, 1981). The second area is the narrow E-W trending Coastal Plain of southern Mainland Kachchh along the Gulf of Kachchh. The third area is the hinterland Quaternary deposits along the river valleys as terraces and fluvial sand bars, and also along the major fault scarps in the form of colluvial fans, alluvial fans, and valley fills with sandy biomicrites and aeolian miliolite.

**Tectonic Geomorphology of Kachchh**

The landscape of Kachchh is characterized by rugged hill ranges having a steeper northern side and a gentle back-slope. Fault-controlled hill ranges are flanked to their north by major E-W trending longitudinal faults, i.e., Nagar Parkar Fault, Island Belt Fault, Kachchh Mainland Fault, South Wagad Fault and Katrol Hill Fault. These faults have played a pivotal role in sculpturing the landscape and are the main cause of the cuesta-like topography with a steep northern escarpments and a gentle southern slope (Biswas, 1971). The northern hill range is mainly characterized by various domes, half domes, anticlines, monoclinal flexures and cuestas. Anticlines and domes ranging in elevation between 190 and 388 m are aligned along the southern flanks of the E-W trending faults. At places they are dissected by oblique cutting subordinate faults of varying trends (NNE-SSW, ENE-WSW, N-S and WNW-ESE) along which various present-day rivers have formed their courses (Maurya et al., 2003).

Many streams in the mainland flow across the hills and flexures, forming incised channels, and cutting the uplifted areas marked by upwarps, flexures and half domes, and maintaining their gradient. The faults at some places separate the hill ranges to the south and the Quaternary plains to the north, and is considered to be neotectonically and seismically active. The youthful nature of the steep to sub-vertical fault scarps is attributed to its periodic reactivation. Transverse faults have divided the E-W trending faults into various segments (Maurya et al., 2003). North of the scarp lies gently north-dipping, colluvio-fluvial deposits, which have clasts of boulders to gravel, and appear to merge with the Quaternary and Cenozoic plains at several places.

**Drainage Pattern**

The drainage pattern in Kachchh Mainland is largely dendritic, and is controlled by the homogeneity in lithology and structure. Around the domes, on the other hand, the drainage pattern becomes radial. Individual streams often show meandering and braided nature, especially in the coastal plain. In the north-flowing streams sharp turns are numerous, which can be explained as stream courses following some pre-existing faults/weak zones that got reactivated. Such reactivations have also led to the formation of knick points along some north-flowing streams. Significant down-cutting has also taken place along the affected channels (Fig. 10).
The complex drainage pattern of Kachchh Mainland is the result of streams switching or abandoning outlets as they cross the E-W trending master faults. It suggests that there is strike-slip movement along the transverse faults. The NNW–SSE, NNE-SSW and N-S trending trellis, angular and straight drainage patterns that have developed in the area, point to the influence of transverse structures. Further, both the higher and the lower order streams trend in NNW–SSE, NNE-SSW and N-S direction, indicating the influence of recent tectonic activities in the area. The response of streams to the transverse lineaments, fractures and transverse faults is seen in the form of sharp angular turns in their courses and at places as beheading of streams.

Fig. 10. Drainage map of Kachchh Mainland.

**Socio-economic Aspects**

Because of the vast desolate Ranns, the large salt-affected plains, the mangrove swamps, the hilly terrain and an arid climate, Kachchh district has a very low density of population. The 2011 density was 46 persons per sq. km (as compared to 308 persons per sq. km in the state of Gujarat as a whole), while the 2001 density was 35 persons per sq. km. With a total of 2.09 million persons, the district’s contribution to the total population of the state is only 3.47%. Kachchh has many religious and ethnic groups. The majority of the inhabitants are Hindus, but the Jains and the Muslims are also numerous. The major occupation for centuries is agriculture and cattle breeding. Despite the low population density, the district is known for engaging a large section of its population in international trade and commerce, especially in the Middle East and East Africa. This generates huge financial resources, which has helped much in stabilizing the economy of the district and improving the life style of the inhabitants. For millennia most households
of the Kachchhis are known to have engaged partly in international trade through sea routes across the Arabian Sea, especially following the Trade Winds. Even today, a visit to many farmlands in Kachchh will surprise a visitor to find womenfolk and elderly people managing the agricultural production system, the younger men mostly managing the trade abroad, or in large metropolis, with periodic visits to home. The enterprising nature of the people and a large outside contact has helped the inhabitants to experiment with innovative ideas in their land management practices, wherever a scope was noticed. Although summer cropping of pearl millet is universal, with low yield, groundnut, cotton and some pulses are also grown extensively during summer monsoon. Wheat and mustard are grown during winter in some pockets with groundwater-irrigation potentials. The most spectacular recent development in agriculture has, however, taken place in diversification to orchard development, especially for national and international markets. Date palm, mango, banana and papaya are now the high-value crops in parts of the Coastal Plain, especially between Anjar and Mandvi. Diversification is also taking place towards growing spices and medicinal plants like cumin, coriander, fenugreek and Isabgol, as also vegetables.

Kachchh is also known for its sturdy cattle population that has thrived on the vast Banni grassland and on the crops and plant resources of the rugged hilly terrain. It has about 0.6 million cattle and buffaloes, and 1 million sheep and goats. Encouragement given to dairy farming and associated value chain development has vastly improved the scope of livestock raising as a means of livelihoods in the district. Although for centuries Kachchh district remained engaged in agricultural and in trade and commerce, the large-scale devastation of life and property during the 2001 earthquake made the state to think about a policy shift from a totally agriculture-based economy to encouraging industrialization, especially utilizing the large barren and otherwise wastelands. Consequently, by 2011 the district became a major hub of small and medium industries. Two large modern sea ports at Kandla and Mundra help in boosting the economy. The downside is that industrialization has affected the coastal ecosystem of the district, especially as the mangroves have almost vanished from near Mundra Port, making the coastal segment more vulnerable to storm surges, tsunamis, etc. Industrial pollution through effluent discharges and atmospheric loads is another major issue to be tackled now.

Bhuj, Mandvi, Mundra, Gandhidham and Anjar are the major towns in the district. Bhuj is the district headquarters, and is well connected with other major cities of Gujarat through road. Bhuj and Kandla are also connected with other parts of India through air. Bhuj has direct air accessibility with Mumbai, the business capital of India with two flights operating every day, while Kandla – the business capital of Kachchh has daily flight connecting Mumbai and Ahmedabad. Kandla is a major port and a ‘Free Trade Zone’ in India. Mundra sea port has the largest container cargo facilities in Asia and is
nurturing the best goods transport business of India. Almost all the villages in the district are well-connected with Bhuj through all-weather metal roads (Fig. 11).

As the connectivity with the rest of the country has improved, Kachchh is gradually becoming a major tourist destination, especially because of the vast salt expanse of the Great Rann, at the southern fringe of which the state now sponsors a “Rann Festival” that attracts tourists from India and abroad. The discovery of a 4000-year old Harappan township at Dholaveera along the north-western fringe of the desolate Khavda Bet, facing the Great Rann draws many tourists, especially as it showcases the advanced water conservation system of those early inhabitants, and the navigability of the Rann during the period. The marshes fringing the Great Rann and the Little Rann attract many different kinds of birds, including the majestic cranes from as far as Siberia, who flock in large numbers during the mild winter, especially in search of good marine food. This has also become an interesting tourist destination. Apart from the above, Kachchh is known for ages for its religious tourism. Two temples at the western end of the mainland at Koteswar and Narayan Sarovar along the Kori Creek, which are dedicated to Lord Shiva and Lord Vishnu, respectively, are mentioned in the ancient Indian scripture, the Mahabharata, as the must-visit places for purification of mind and soul. Another very old temple dedicated to Goddess Durga at Mata-no-Madh (to the west of Bhuj) is among the 16 most-sacred temples of the Goddess Durga in the Indian Subcontinent, and attracts huge congregations from across the country during special religious festivals. The Tertiary clay beds in the surroundings of the temple exude a soothing fragrance. For millennia, therefore, the clay has been used as a natural incense material for temples in
India and abroad, this being a major export item to the Greek and Roman empires during their heydays. Sadly, over-exploitation of the clay has now almost exhausted the reserve. Lakhpat at the north-western end of the mainland was a known seat of higher learning during the time of invasion by Alexander the Great and up to the Early Century ADs, which was described in some details in the writings of the celebrated Chinese visitors of the time. It was also a port en-route to Sind. Repeated earthquakes and wars destroyed the site, but it now attracts some informed tourists. Apart from the above, edifices in Bhuj and Mandvi also attract many tourists.

Bhuj town, with a population about 225000, is centered around the large Hamirsar Tank, which serves as a water storage during the dry months. In the middle of the lake lies a small island (Rajendra Park). The city's most visited sight, the palace of the king of Kachchh, lies adjacent to the water tank (Fig. 12). It consists of several buildings constructed in different centuries, each with its own style and character. The Aina Mahal (the mirror palace) was built in AD 1752 and includes a small museum displaying some of the king's possessions. The younger Prag Mahal, with its massive tower reminiscent of the architecture of a European church, dominates the landscape of Bhuj. A visit to its halls shows the taste of the then king, but the damages done by the massive earthquake of 2001 and the neglect over time, have left the building in a dilapidated condition. The oldest part of the palace is the Durbar Garh. Although it has been in ruins for a long time, some of its walls still stand with beautifully ornamented and latticed windows.

![Fig. 12. Aerial view of Hamirsar Lake and surrounding areas of Bhuj town.](image)

Kachchh district has now a university, the Krantiguru Shyamji Krishna Verma Kachchh University, which is located at Bhuj (Fig. 13). It offers education in different branches of Science, Arts, Commerce and Engineering. The University was established in March 2003 with 6 affiliated colleges, but now has 39 affiliated colleges and 14 on-campus academic departments, including the Department of Earth and Environmental Science. The post-graduate (PG) courses run on the campus are for the degree of MBA, MSW, M.Sc. in Chemistry, Geology, Environmental Science, Computer Applications and
Information Technology; M.A. in Gujarati, Sanskrit, Economics, English, Archeology; M.Com; and M. Phil in Gujarati, Economics, Sanskrit and Education. The PG student strength in the campus is about 1000. The university also runs Ph.D programmes in all the departments. About 125 students are currently pursuing Ph.D. Apart from the above courses almost 6,000 students are studying B.A./B.Com and M.A./M.Com courses in distance education mode.

Some other research facilities are also located in the district, especially in and around Bhuj. These include the Gujarat Institute of Desert Ecology (GUIDE), a Regional Research Station of Central Arid Zone Research Institute (CAZRI), and a sub-station of Gujarat Agricultural University.

The main building of the KSKV Kachchh University.
B. DESCRIPTION OF THE FIELD SITES

Day 1
Arrival at Bhuj
Stay at Bhuj.

The first day of the field trip will be spent on a pre-field discussion at KSKV Kachchh University on the areas to be visited, and on the logistics, etc., followed by a visit to the Geological Museum in the University, and then a field visit to some interesting sites around Bhuj. The places to be visited during the field trip are shown in Fig. 14.

Fig. 14. Image-map of Kachchh district, showing the routes of field traverses in Kachchh Mainland.

Geological Museum, Department of Earth and Environmental Science, KSKV Kachchh University

The Department of Earth and Environmental was established in the year of 2008. The major physical resources of the Department include a Remote Sensing and GIS Laboratory, a Petrography Laboratory, an Environmental Chemistry Laboratory, some geological and geographical field surveying instruments, a library with spacious reading
rooms for students and staff members, and a state-of-the-art museum of geological specimens, including rocks, minerals, fossils and 3-D models of interesting geological features. Some of the displayed fossils of marine and land reptiles and mammals of Tertiary and Jurassic periods, collected from different parts of Kachchh district, are rare.

Field Trip

Stop 1: Khari Gorge on Kodki Road

A significant young landform on the rocky platform around Bhuj town is a gorge along the River Khari, found 4 km to the west of Bhuj town on Bhuj-Kodki road (Fig. 15). The NE-SW flowing Khari River cuts the sandstone bedrock into a deep gorge for a kilometer in length. This section of the river reveals a deep and narrow gorge with four different tectono-erosional terraces in sandstone, depicting slow tectonic uplift and lateral erosion. The uplifted bedrock terraces have many pot-holes and flutings, indicating high energy conditions during the past climate. The feature is useful in understanding the tectonic and climatic evolution of Kachchh Mainland.

Stop 2: Kodki Road Fault and Dyke

The road from Bhuj to Kodki village is full of interesting geological structures. The road-cutting at ~10km from Bhuj exhibits many transverse faults (Fig. 16). Many text-book-type faults with dip-slip movements and down-throw of few cm to a metre can be noticed at the site. A typical dolerite dyke of 5-6 m thickness is also seen to be intruded along the N-S trending transverse fault (Fig. 17). The rocks exposed at the site are sandstones and
shales of Cretaceous age. These normal and reverse faults with insignificant down-throws are associated with a NNE-SSW trending ‘Median High’, a structural high across the Kachchh basin. Such faults are known as hinge faults.

**Stop 3: River Section near Rata Talab on Bhuj-Tapkeswari Temple Road**

The road from Bhuj to Tapkeswari Temple to the south of Bhuj town runs along the dip slope of the Jurassic, Cretaceous and Tertiary formations. The E-W trending Katrol Hill Fault (KHF) appears as a simple south-dipping fault plane, and also as an intensely-flexured zone at places. The KHF plane is so conspicuous that its hanging wall shows the older Jurassic sandstone, and the footwall block shows the Cretaceous sandstone, indicating a reverse fault (Fig. 18). The common fault plane features like striations and slickenslides are well preserved on the fault plane. The flexure zone at the site is highly complex and structurally complicated as ductile to brittle deformation is very common at the site.

![Fig. 16](image16.png)

Fig. 16. A N-S trending transverse fault on Bhuj-Kodki road with showing more than 1 m down-throw.

![Fig. 17](image17.png)

Fig. 17. A dolerite dyke intruding the Cretaceous Sandstone beds on Bhuj-Kodki road.
Stop 4: Tapkeswari Temple

The receding scarps of the hill on which the old Tapkeswari Temple has been built belong to the 65 km long Katrol Hill Range (Fig. 19). Geologically the area is highly faulted with some transverse faults that have shifted the KHF further north. The scarps are almost 2 km to the south of the Katrol Hill Fault (KHF), which was observed at Stop 3. Some textbook-type faults with horst and graben structures can be noticed at the site. Prolonged uplift along the KHF and erosion has resulted in such topographic peculiarities (Fig. 20). The streams from the scarp slopes show several knick points as evidence of neotectonic movements (Fig. 21). The formation of a cave in the sandstone beds at the top of the hill could be due to weathering and erosion along the bedding planes (Fig. 22). The name Tapkeswari came from the trickling of water along rivulets from the scarp base.
Stop 5: Khatrod Hill on Bhuj-Kukma Road

The most elevated part of Katrol Hill Range occurs to the south of Kukma village, where the hill is called Khatrod Hill. The site provides some good examples of fault scarp morphology and tectonic landforms. The ideal features associated with a fault scarp, like the crest, the scarp face, the colluvial fan slope, wash slope, triangular facets and the alluvial plain surface can be identified at the site (Fig. 23). The scarp face exposes the Jurassic rocks (Jhuran Formation) with alternate sandstones and shale beds. The Quaternary deposits in the area also show various aeolian to fluvial episodes. A structural dome along the KHF, the Khatrod dome, can also be seen here. The older beds are exposed in the core of the eroded dome and the anticlines here. The temple at the top of the hill is called the Ashapura Temple.

Fig. 21. Knick point along a stream cutting across the Katrol Hill Fault near Tapkeswari Temple.
Day 2
Bhuj to Nirona, Banni, Simri Vandh, Kaladungar Range and back
Stay at Bhuj.

The day will be spent in exploring the geological and geomorphological features to the north of Bhuj town up to Pachchham Island.

Stop 1: Nirona Canyon

Nirona River is essentially a bedrock river that passes through the Jhura Hills (a part of the Northern Hill Range in Kachchh Mainland). A large geological structure, known as the Jhura Dome, has formed the hill. As the river has cut its course through the hill, it has incised its bed into the Jurassic sandstones and shales of Kimmeridgian and Tithonian age in the core of the dome. The rocks vary in colour from black to brown, red and yellow, providing a picturesque view of the valley (Fig. 24). A number of faults and intra-formational unconformities, primary and sedimentary structures and trace fossils...
could be noticed at the site. This is an ideal location for studies on sedimentology and structural geology. Several streams here follow the structural lineaments and lithology.

![Image](image.jpg)

**Fig. 24. Jurassic sandstone and shale beds of different colours exposed along the Nirona River valley.**

**Stop 2: Banni Plain**

The Banni Plain is a unique geomorphic surface having a maximum elevation of 10-15 m from msl and 8-10 m from the Great Rann of Kachchh. The dominantly silt and clay layers of the plain are very saline and allow only halophytic grasses and shrubs to grow on the surface. Groundwater is also very saline. However, during the monsoon rains the silt and clay layers, topped by a thinner fine sand deposit, restrict the percolation of water underground, and help to form small pools of fresh water, thus making available some potable water for the sparsely settled people and their livestock in this vast saline plain. Two such types of water body, known locally as the ‘Dhandh’ (for a large water body) and the ‘Thath’ (for a small water body), can be found in the area. The larger ‘Jhils’ (large pools of water) within the plain are typically the salt marshes along the lowermost parts of the Banni, which also receives rainwater during the monsoon months, and become less saline. After the rainy season and till the end of winter these Jhils abound with aquatic life and so attract many different kinds of birds from as far as Siberia in search of good food. During good monsoon years the Jhils get flooded and inter-linked, which cuts off the plain from the mainland in the south and the Pachham Island in the north. The Jhils gradually dry up as the summer sets in.

The natural grassland of the Banni also depends on the meagre monsoon rains, and provides good fodder for the livestock. The higher part of the Banni, with a less saline soil, hosts some of the best grass species (Kar, 2011), which is a boon for the local livestock raisers, called the ‘Maldharis’. These people have settled here several centuries
ago, and have preferred to live in this largely inhospitable and secluded plain with their cattle and buffalos, sheep and goats, despite all the hardship for a livelihood based mostly on milk and milk products that they sell in the mainland. Through their toil and constant care they have developed one of the best cattle breeds in the region that is not only drought-hardy but also high milk yielder. Unfortunately, the Banni grasslands are now getting largely invaded by thorny bushes of mesquite (Prosopis juliflora), an aggressive coloniser that has no fodder value, and that does not allow grasses to grow in its shade. Consumption of its leaves and pods by the livestock leads to mortality. The plant is not native to Indian sub-continent, but was introduced in the 1940s from Latin America, mainly for the purpose of greenery of the Thar Desert and for fuelwood. Unfortunately, the plant proved to be a menace. Because of its very fast growth, strong and proliferating roots and excellent adaptability to saline and drought conditions, mesquite has replaced the best quality grasses over much of the area (Kar, 2011). Although its dry branches have fuel value, these hardly had any special attraction for the Banni inhabitants. The state is now trying to uproot the mesquite clumps from the Banni plains by using machines, but the battle is proving difficult and long.

**Stop 3: Paiya Dome**

After crossing the Banni Plain one enters the rugged hilly terrain of Pachham Island (Bet) in the Great Rann of Kachchh. A small structural dome situated between Kaladungar and Goradungar hill ranges in the island, and called the Paiya Dome, is of some interest (Fig. 25).

![Fig. 25. A distant view of Paiya Dome between Kaladungar and Goradungar hills. It provides a good example of doubly plunging anticline and syncline structures.](image)

Geologically this structure consists of a series of small double-plunging anticlines and synclines. Here the younger Goradungar Formation, containing fossiliferous limestone and sandstone are exposed abutting the secondary ‘Goradungar Fault’ that passes between the two ranges. The isolated domal uplift is a result of transverse faults that dissect the Kaladungar Fault, a part of the Island Belt Fault. The Quaternary deposits along the northern face of the dome show signs of continuous upward movement as rising
anticlines, above which the deposition of some aeolian dunes has formed miliolitic limestones (sandy biomicrites). Quaternary fluvial deposits in the large valley between the two ranges have reworked miliolites. During the late Pleistocene to Holocene period some alluviation have taken place in the island, making the land suitable for early civilization, as discovered at a site known as ‘Kuran archeological site’.

Stop 4: Bandi River Section

The river section here provides evidence for past wet climate during the late Quaternary period. The high river banks exhibit Tertiary rocks (mostly Miocene) overlain by un-assorted Quaternary debris, with sediments ranging from boulders to sand and silt (Fig. 26). This suggests a fast depositional phase, possibly involving some unusually large floods and debris flows. The site is along a valley at the back-slope end of a gently-sloping cuesta of the Kaladungar Range. The mixed debris flow deposits, with intercalation of coarse to fine sand of channel bar deposits that are seen as lenses along the vertical banks suggest deposition by high-intensity flash floods during a wetter climate in the past, as well as debris flow. The exposed Tertiary bedrocks indicate the base level of erosion, following a slow uplift in the area. The meandering course of the river downstream of the site is controlled by activities along the transverse faults in later periods, which have shifted the river courses at places.

![Fig. 26. The Bandi River section in Pachham Island, exposing Quaternary deposits over the Tertiary rocks.](image)

![Fig. 27. A symmetrical plunging fold in sandstone, exposed along the northern bank of a stream near Simri Vandh.](image)

Stop 5: River Section near Simri Vandh

Further to the north, and near the Kaladungar Hill range, the stream sections expose the flexures in Jurassic rocks of the Goradungar Formation. Near Simri Vandh village the northern bank of a stream has exposed a symmetrical plunging anticlinal fold in the Jurassic sandstone beds (Fig. 27). Such flexures in the Jurassic rocks are common in the Kachchh Mainland and in Pachham Island, especially due to early Tertiary reversal movements of the horst blocks in the Kachchh basin. It is because of this that the rocks
have duel behaviour of ductile and brittle deformations at places. The limbs of the fold and the river beds expose the Raimalro Sandstone member, which is very rich in different trace fossils. Rizocorralum and diplocraterian are very common, indicating their deposition in a shallow shelf to sub-littoral condition during the Callovian to Oxfordian time.

**Stop 6: Babia Peak of Kaladungar Hill range**

Babia peak of Kaladongar hills (meaning Black Hill in local language) is the highest peak in Kachchh with a height of 462 meters (Fig. 28). Located at the northern end of Pachham Island it occurs along the northern faulted border of the island, conspicuously marking the boundary between the rugged hilly terrain and the vast Great Rann of Kachchh (Fig. 29). The oldest rocks in Kachchh are exposed along the Kaladungar Hill range as the Kaladungar Formation. It is composed of very hard, yellow to gray, nodular limestone. Excellent three sets of joints, and gravity collapse linear valleys can be noticed here. The older rocks of this formation include alternate bands of sandstone, siltstone and conglomerate while the younger ones in the upper part consist of massive sandstone and bands of calcareous sandstone. The younger Goradongar Formation overlies the Kaladungar Formation, showing the change in rock assemblage from sandstones to flaggy limestones and shales. The rock characteristics suggest that depositions took place in a near-shore environment. The southern part of the hill contains hard limestone of Upper Kaladungar Formation. The top of the Babia Hill shows vertical scarps that suggest reactivation of the Island Belt Fault during the later phases of emergence of the Kachchh landscape. There is a laccolithic intrusive body in the core of the dome-shaped hill. Basic (doleritic, andesitic and lamprophyric) dykes are common in the area.

![Fig. 28. A view of the N-facing IBF scarp on the Babia Peak of Kaladungar Hill range.](image)
Stop 7: The Great Rann of Kachchh

Descending from the hill, one approaches the vast expanse of the Great Rann of Kachchh (Fig. 30). The apparently stable-looking surface of the salt-encrusted Rann surface is highly tricky for venturing into it, as water occurs just below the surface, and often bogs down an un-suspecting intruder (Fig. 31). Only at some locations the water level goes down during some dry months of the year, and makes the surface trafficable. Such locations are known mainly to the local inhabitants who, in earlier time, used to move across the Rann with their livestock and other supplies for trading purpose. As has been described earlier, the northern end of the Great Rann is slightly elevated due to the Allah Bund Uplift (Fig. 32). Once on that surface, one is able travel more freely on the muddy surface.

Constructing road across the Great Rann is, therefore, difficult. Maintaining a road in its saline marshy environment is still more difficult. However, overcoming all the difficulties, India has constructed a few defence roads across the Great Rann for defending its border.
Fig. 31. Dried up, but deceptive mud polygons along the fringe of the Great Rann of Kachchh near Kala dungar Hill.

Fig. 32. The youthful topography of Allah Bund uplift.

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**Day 3**

**Bhuj to Dhinodhar, Lakhpat and Narayan Sarovar**

**Stay at Narayan Sarovar.**

The day three of the field trip will be spent in exploring the fascinating landscape to the west of Bhuj and up to the western tip of Kachchh Mainland along the bank of Kori Creek that once used to carry the waters of the Indus River. The night stay will be at Narayan Sarovar, which is described in the early Indian literature, the Mahabharata, as one of the holiest places in India.

**Stop 1: Dhinodhar Plug**

Dhinodhar Hill, with a height of 386 m (the second highest peak in Kachchh district) is located about 17 km to the NE of Nakhatrana town, and is an old volcanic plug (Fig. 33). The drainage lines from the hill have developed a radial pattern, and the steep hill slope is covered with scree of cuboidal blocks of basalt. The plug was formed inside an abandoned and eroded volcano, and came into existence during Late Cretaceous period as
an eruptive centre of the Deccan Trap lavas. The plug is composed of a closely-spaced cluster of basaltic hills, among which the Dhinodhar peak is the highest. The trekking route for Dhinodhar peak starts at Thān, the ancient ‘Jāgir’ of the Princely state. Excellent columnar joints in basalt can be seen in the valley that leads to the hill top (Fig. 34). Mostly the fine-grained thoeïtic basalt was erupted, but occasionally the early-crystallized olivine xenoliths could also be noticed. The lava cuts across the Jurassic rocks and finds its way close to the major Kachchh Mainland Fault.

Stop 2: A Hillock near Dhori Village on way from Dhinodhar to Guneri

Near Dhora village, on way to Guneri and Lakhpat, one can stop at a small hillock formed of the highly-eroded shales of Jurassic Formation. Climbing on to the hillock one can have a panoramic view of the N-S transect across the Northern Hill range of Kachchh Mainland Uplift. This gives a good idea of the regional topography that runs with the structure. To the west one can see a gentle anticlinal flexure of the Keera Dome at the northern edge of the tilted uplift as well as the conical hill of Keera Dungar, which is a plug that had intruded through the master fault, KMF. To the south extends the gently dipping back-limb of the anticline, followed further south by a high escarpment called the Jaramara Cliff that exposes the rocks of Callovian to Oxfordian and Kimmridgian ages, with a protective cap of sandstones of the Uppermost Jumara Formation.

Stop 3: Jumara Dome

The Jumara domal structure is another important structure in the chain of folds in the KMF deformation zone, and is magnificently exposed like a chopped onion, which marks the climax of a syn-rift stage. The formation is predominantly greenish gray shale with thin fossiliferous limestone/marl bands and occasional fine-grained sandstone beds of mid-Callovian to early Oxfordian (Mesozoic) age, constituting the Jumara Formation, which were deposited during the highest sea-
level stand in Mesozoic. The top 30 m is glauconitic with oolitic limestone bands, distinguished as Dhosa Oolite Mbr. This member is a treasure house of ammonite fossils, which attracted the attention of British geologists to this area during the early 19th Century. A thin sill of basalt is seen below the Dhosa Oolite Mbr, going round the dome. Towards the centre of the dome the road crosses the shale - limestone boundary between the Jumara and the Jhurio (Bathonian-Early Callovian) formations (Fig. 35). The entire sequence is very rich in fossils from ammonite to coral. At the core of the dome several coral biostromes are present. The northern limb of the dome dips steeply to the N with a hard dirty brown limestone bed. This limb, draping the Kachchh Mainland Fault (KMF), forms a near-vertical E-W ridge, beyond which stretches the Banni plains.

Fig. 35. The contact between the Jhurio and the Jumara formations, exposed in the core of the Jumara Dome.

**Stop 4: Ghuneri Structural Dome**

Ghuneri structural dome is in the northwestern corner of Kachchh Mainland Fault near Ghuneri village, and is distinguished by escarpments facing the Rann surface to the north. A zone of second order faults is exposed along the foot of the marginal escarpment which is considered as the KMF zone (Fig. 36). This marginal fault is exposed in segments. Where exposed, steeply upturned (ankle fold) Tertiary strata are juxtaposed with steeply down-folded (knee fold) Mesozoic strata. Such fault ridges are offset at places by tear faults. This is a distinct geological and geomorphic structure where the streams follow circular paths along the lithology, and form a circular drainage patterns.
Fig. 36. The western termination of the KMF at Guneri, dissected at places by transverse faults.

Day 4
Narayansarovar to Koteswar, Naliya, Mandvi and Bhuj
Stay at Bhuj.

On the fourth day of the field trip the terrain along the Coastal Plain bordering the Arabian Sea will be explored.

Stop 1: Narayan Sarovar

Narayan Sarovar near the eastern bank of the Kori Creek is an ancient holy place for pilgrimage for the Hindus, and is described in the Mahabharata as having a pond fed by natural spring, where bathing ensures purity of body and mind. Unfortunately, the natural spring has now ceased to exist, possibly due to very high exploitation of groundwater in the surroundings. The bathing facilities have been spruced up to cater to the needs of large number of devotees that gather here annually. The Sarovar (a Sanskrit word for lake) and the temple complex associated with it is situated on a low limestone terrain detached from the mainland, and surrounded by tidal mud flats associated with the Kori Creek. The lake water is always sweet and rarely gets dry, probably due to the aquifer in the synclinal structure in Tertiary rocks here.

Stop 2: Koteswar

The temple at Koteswar is located on a rocky promontory on the bank of the Kori Creek, 1 km to the southwest of Narayan Sarovar. This is also a very old pilgrimage site, and is described in the Mahabharata as having very high spiritual significance. The
Creek is about 12 km wide here, and the coastal tract from Lakhpat to Koteswar and further south and east up to Jakhau is muddy with an inter-tidal area that is rich in marine life and mangroves.

Several other creeks between Kori Creek and India’s border with Pakistan along the Sir Creek are extremely rich with fish and other marine life. In ancient times, the maritime route for trade and commerce from Sindh (now in Pakistan) to the cities along the west coast of India, and to the African shores used to follow the Kori Creek via Sindri, Lakhpat and Narayan Sarovar-Koteswar. The devastating earthquake of 1819 in the Great Rann of Kachchh created a huge mud wall across the creek between Sindri and Lakhpat, and disorganised the steam, the Puran, through it. The high mud wall was named by the inhabitants as “Allah Bund” (i.e., a dam created by the Almighty). Sindri town and the Puran’s course from there to the Allah Bund got submerged, while the stream segment south of the Allah Bund to Lakhpat and beyond got tilted, but survived. In between, the river lost its navigability in the up-thrown segment. According to the descriptions of Greek historians, Alexander the Great might have sailed through either Kori Creek or any of the many other creeks in the Indus Delta during his campaign in the Indus plains around 325 BC. One of the detachments of his army, while returning to Greece, might also have experienced tsunami due to a major earthquake along the coast to the west of present-day Karachi, and might have suffered some losses. While coastal segment to the west of Kori Creek and up to Sir Creek is an unfinished delta, the segment from Koteswar to Jakhau in the east is characterised by several features of drowning, including a ria coast (Kar, 1993; 2011).

**Stop 3: Coastal Dunes at Pinjor Pir**

About 5 km to the north of Narayan Sarovar a number of 10-12 m high coastal sand dunes can be observed along the eastern bank of the Kori Creek. The dunes are fine-to-medium-grained, partly vegetated, and are oriented SW-NE, in the direction of the dominant summer monsoon wind. They rest partly over the narrow mud flat along the Creek, and partly over the Tertiary limestone terrain inland.

**Stop 4: Kakdi River**

Continuing the journey south-eastward towards Mandvi, the road crosses a small stream with a rocky bed, the Kakdi River (Fig. 37). It exposes the Deccan Trap basalt and the lower part of the Paleocene Formation, while to the north of the road bridge, shales rest over the eroded, partially lateritised surface of the Deccan Trap, which is the basement of Tertiary Formations in western India. This formation overlaps the Late Paleocene Mata-no-Nadh Formation at this site.
Stop 5: Rakhadi River

The deeply incised ephemeral valley of the Rakhadi River in the near-horizontal Eocene Limestone beds provides a spectacular site of a canyon-like feature with vertical rocky banks (Fig. 38). Walking away from the road and by the right-hand side of the river one finds a palaeo-channel filled with Quaternary conglomerate and sand on the cliff. Walking 500 m upstream, large caves are seen in the massive foraminifera-infested nummulitic limestone (Fig. 39). Several such caves of different sizes can be noticed upstream of this site, which occur at the base of the clifffy bank of limestone. Such mid-Eocene cavernous limestone beds proved to have excellent reserves of oil & gas in the western offshore fields.
Stop 6: Wayor on Naliya Road

At Wayor village, one can walk up the river valley for 1 km to a 12 m high cliff section. This section is known as the Chattian type section, and is internationally recognized as an important reference section for the yellow, bedded, and bio-turbated limestone, inter-bedded with thin calcareous shale, rich in forams like Miogypsina and Spyroycephus. It also exposes other mega-fossils, including ichno-fossils.

Stop 7: Khari River

Turning E from the main road on the Khari River, the type section of Early Miocene (Aquitanian) Khari Nadi Formation (yellow and variegated fine sandstones) can be observed resting over the highly fossiliferous blue clay with molluscs.

Stop 8: Mandvi Beach

Mandvi, the second largest town in Kachchh district, has a wide beach, which is composed of a foreshore and a backshore, followed landward by a raised beach of 2-3 m height, the foredune and then a tidal mud flat at its back and a saline sand flat (Fig. 40). The coastal alluvial plain occurs beyond it. Longshore drift is present along the coast, which carries the sand eastward to form a spit between Mandvi and Mundra. The raised beach appears to be related more to neotectonic activities associated with the Median High than to eustatic change of base level (Kar, 1993).

The return journey from Mandvi to Bhuj will be through the hilly terrain across the Katrol Hill range.

Fig. 40. The foreshore, the backshore, the raised beach and the foredune at Mandvi.
Day 5  
Bhuj to Habo Dome, Kas Range, Lothia Nala and back  
Stay at Bhuj.

On the 5th day of the field trip we propose to explore the terrain to the north-east of Bhuj, which is nearer to the epicentre of the devastating earthquake of 26 January 2001. The traverse route provides some excellent examples of the geomorphic expressions of a tectonically active large dome and anticline, especially along the escarpments, stream valleys, etc.

**Stop 1: Zikdi Road Cutting**
The first stop at Zikdi road cutting is on the south-western fringe of Habo Dome, which is roughly of the size of 16 km (Fig. 41). This domal structure, upwarping the Mesozoic rocks in the form of a cluster of hills, occurs roughly between the Khari River in the west and the Kaswali River in the east, both exploiting transverse faults bordering the Habo Dome, and across the Kachchh Maniland Fault, and both debouching into the Great Rann of Kachchh in the north. The dome’s fringing curvilinear escarpment in the east, roughly along the Kaswali River, leads to the Kas Hill Range. The rocks exposed at the site are sandstones of upper Jhuran formation formed in a deltaic to fluvial depositional environment. The site is at the junction of two faults. One to the north of the scarp runs E-W, while the other, a transverse strike-slip fault, dissects the E-W trending fault. It displaces the escarpment by several metres along the N-S trend. To the north, a large cluster of hills in dome shape characterises the Habo Dome.

![Fig. 41. The southern flank of the Habo Dome, where the Kas Hill provides a cuesta landscape.](image)

**Stop 2: Dhrang, at the core of Habo Dome**
The path along a small stream to the south of Dhrang village leads to a huge exposure of laccolith intrusion in the core of the Habo Dome. The rock type is gabbro, which has a sharp contact with the Mesozoic limestone bed (Bathonian) above (Fig. 42). The Mesozoic rocks at the site seem to be dipping due north. The sedimentary sequence at the site consists of bands of Dosa oolite (Jumara Formation), golden oolite and thickly bedded limestone (Jhurio Formation). The bedding of the limestone appears up-wrapped due to the igneous intrusion. Small micro-faults are seen to
displace the limestone beds at several places. Towards the northern and southern margins of the intrusion the limestone beds dip by 3°/290°. Towards the centre, the beds are almost horizontal. The laccolith-like intrusion is approximately 20 m thick in the centre and gets reduced considerably towards the north and the south. The contact between the intrusion and the overlying limestone is sharp but protrusion in the form of small sills, appophysis, etc., along and across the bedding planes are noticed. At places the contact zone is marked by the presence of suspected serpentine (green). The intrusion is fine-grained along the contacts, but becomes coarse-grained towards the centre, where pyroxene crystals of 1-2 cm size can be noticed. The igneous intrusion is highly jointed; the joints are vertically disposed, suggesting that the cooling front was horizontal. The joints become more regular and closely-spaced in the coarse grained rock near the centre of the plug. Towards the northern end, there are a couple of large (> 50 cm) angular xenoliths of limestone in the intrusion. The eastern and western limits of the domes are marked by N-S transverse faults. Such distribution indicates a close genetic relationship of magmatism and tectonism in this part. The second mode of uplift is caused by the sub-crustal intrusions. The existence of laccolith at Dhrung is suggestive of shallow level of uplift of the sedimentary strata.

Fig. 42. A gabbro laccolith in contact with Mesozoic limestone bed in the core area of Habo Dome.

Stop 3: Foothills of the Kas Hill Range
The Kas Hill Range to the east of Habo Dome is an anticlinal ridge with a prominent N-facing escarpment in the Mesozoic rocks (Jumara Formation), roughly from near Lodai in the west to the vicinity of Jawaharnagar in the east (Fig. 43). The escarpment is followed southward by the dip slope of a cuesta that forms the southern limb of the large Kas anticline, the northern limb of which was eroded out.
The narrow Kas Hill anticline occupies the entire length of the eastern half of the main flexure, and retains mostly the original form of the flexure. It has a chain of domes along its axis, the most important among which is the Kas Hill Dome and the associated Kas Hill Fault, which branches off from the Kachchh Mainland Fault (KMF) as a feather fault, with a tilted block between them. It is believed that movements along the KMF resulted in the major earthquakes of 1819 and 1956. Faults are much less in number further to the east. Only a few NE-SW or NNE-SSW oblique faults are seen across the Kas Hill anticline.

**Stop 4: Lotia River Gorge**
Lothia River, originating from the Kas Hill, traverses through the hill’s piedmont zone in the middle reaches, and then ends up along the margin of the Banni Plain. Like the other north-flowing streams, Lothia River also forms an alluvial fan before it meets the Banni Plain. The river flows through Bhuj Sandstone in its middle and lower reaches. At the mouth of the river, thin Quaternary cover is present in the form of valley fill sequences. As the river crosses the north dipping scarp of the KMF, it abruptly incises Bhuj sandstone beds by about 11 m and forms a gorge (Fig. 44). Here the river behaves like a fault-controlled channel.

**Day 6: Depart from Bhuj.**
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B4: Geomorphological Field Guide Book on
KASHMIR HIMALAYA

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Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.

### Itinerary

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<td>Breakfast, Srinagar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Srinagar</td>
<td>Pahalgam</td>
<td>90</td>
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<tr>
<td>Day 7</td>
<td>18 November 2017</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>Breakfast, Srinagar</td>
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<tr>
<td></td>
<td></td>
<td>Srinagar</td>
<td>Delhi</td>
<td>600 (aerial)</td>
<td>Departure</td>
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</tbody>
</table>
A. Kashmir Himalaya: An Introduction

The field guide book is a part of the 9th conference of International Association of Geomorphologists to be held at New Delhi, India, from 6-11th November 2017. The guidebook consists of brief descriptions of the geomorphic sites to be visited during the conference field trip to Kashmir Himalaya, (Fig. 1 and 2). Since the participants would be visiting various locations in Kashmir Himalaya, a brief geomorphic description is provided on the landscape evolution related to the history (geology), structural setup and to geomorphic features.

Fig. 1.
Locations to be visited in Kashmir Himalaya.
Fig. 2.
Landsat-ETM image subsets showing the major spots to be visited during the excursion (a) Sonamarg and Thajwas, (b) Machoi Glacier, (c) Wular Lake, (d) Hirpur (Shopian), (e) Pampore and (f) Srinagar.
HIMALAYA
Mountain belts created by continental collision represent the most dominant geologic features on the surface of the Earth. The Rockies and the Appalachian belt in North America, the Andes in the South America, the Ural mountains in central Eurasia, the Alps of Europe and the Himalayas are some of the best examples, each extending for thousands of kilometers. A great deal of attention has been paid to the evolution of these mountain belts since the advent of plate tectonics. The youngest and perhaps the most impressing of all the continent-continent collisional belts on the Earth is the Himalayan orogen; its evolution has long been subject of discussions (Gansser, 1964; Molnar and Tapponnier, 1975; Bhat, 1987; Treloar and Searle, 1993). The Himalayan mountain building is the product of collision between India and Eurasian plate that began during the Eocene epoch and is considered to be one of the major tectonic events in the Cenozoic era and a live example of collision mountain belt as the process of mountain building is still active, forming the highest range and plateau in the world (Molnar and Tapponnier, 1975; Molnar and Chen, 1977).

The Himalayan mountain belt extends over ~2500 Km from northwest to northeast with a variable width of 230 to 330 km, terminating at both east and west ends with syntaxial bends. Based on the works of Burrard and Hayden (1932), Wadia (1931), Bordet (1961), Gansser (1964), Le Fort (1975), Windley (1985), Hodges (2000), Steck (2003), DiPietro and Pouge (2004), the Himalayan terrain from south to north has been conventionally divided into sub parallel tectono-stratigraphic subdivisions: Sub-Himalaya or Outer Himalaya, Lower Himalaya or Lesser Himalaya, Higher Himalaya or Greater Himalaya, and Trans Himalaya or Tibetan Himalaya.

The dividing planes between these subdivisions are the thrusts of regional dimension with varying tectonic activity (Gansser, 1964; Valdiya, 2002) and each subdivision has a characteristic stratigraphy which is hardly co-relatable with adjacent zones (DiPietro and Pouge, 2004). From south to north, the classic bounding faults are: the Main Frontal Thrust (MFT) between the Indo-Gangetic alluvial plain in south to the Outer Himalaya in north, the Main Boundary Thrust (MBT) between the Outer Himalayas and the Lesser Himalayan sedimentary zone (LHSZ), the Main Central Thrust (MCT) between the Lesser Himalayas and the Higher Himalayan crystallines (HHC); the South Tibetan detachment system (STD) between the Higher Himalayas and the Tethys Himalaya, and finally the Indus-Tsangpo suture zone (ITSZ), which marks the northern limit of exposed Indian plate rocks. Along each of these thrusts, tens to hundreds of kilometers of the displacement between India and Asia have been accommodated (Gansser, 1964; Powell and Conaghan, 1973; Seeber and Armbruster, 1981; Schelling, 1992; Treloar et al., 1992; Srivastava and Mitra, 1994). All three zones exert a major influence on the creation of the unique geomorphic architecture of the Himalaya.
Kashmir Himalaya

Neogene–Quaternary intermontane basins occur throughout the Himalaya and southern Tibet. Of the numerous intermountain basins in the Himalaya, the Kashmir basin with distinct NW-SE asymmetric disposition, juxtaposed between Zanskar mountain range in the east-northeast and Pir Panjal range in the west-southwest (Fig. 3), forms a larger segment of the NW Himalaya with basin and range topography. The Kashmir basin is believed to have evolved in the late Miocene by shifting of the NE thrust complex from the base of the Zanskar Himalayan side to the southwest forefront of the Pir Panjal range (Burbank, 1983; Burbank and Johnson, 1983); as a result, the NE thrust complex was replaced by the existing structural system (basement complex-MBT/MCT). This was followed by accumulation of low energy fluvio-lacustrine sediments (Karewa) that constrain initial timing of valley formation to ~5–4 Ma (Burbank and Johnson, 1983; Burbank and Raynolds, 1984). Bhat (1982) proposed a rift-reactivation model to explain the formation of the Kashmir basin along two deep-seated faults, i.e., the Panjal thrust from the west and Zanskar thrust from the east. However, recent work suggests that the Kashmir basin evolved as a result of movement along basement dextral strike-slip fault (Alam et al., 2015a,b).

Several thrust faults have been delineated in southwest of the Pir Panjal range including the MCT/Panjal, MBT/Murree, Riasi, and Kotli thrusts (Thakur et al., 2010); as a result, the zone has a complex pattern of faulting (Fig. 3). The southern-most deformation front of Kashmir Himalaya is defined by an active fold belt known as Surin-Mustgarh anticline that extends from river Beas in southeast to Jhelum in the northwest. Furthermore, several out-of-sequence faults have been identified and delineated between Himalayan Frontal thrust (HFT) and Main Boundary thrust (MBT). These include the Riasi thrust (RT), the Kotli thrust (KT) and the Bagh-Balakot fault (BBF). The latter was the source of Oct-2005 Mw 7.6 Muzzafarabad earthquake (Kaneda et al., 2008; Hussain et al., 2009; Thakur et al., 2010), which claimed more than 80,000 lives. No faulting was known north of...
the MCT/Panjal thrust or MBT/Murree thrust except a high angle thrust fault (reverse) with an average northeast 60o dip and NW-SE strike length of ~100 km (Madden et al., 2010, 2011; Ahmad and Bhat, 2012; Ahmad et al., 2013, 2015; Ahmad, 2014). The unrelenting competition between deposition, erosion and tectonic activity produced most of the geomorphic features in the Kashmir basin.

Kashmir basin is spread over an elevation ranging from the minimum of ~1560 meters to the maximum of 5550m amsl. The maximum hydrographic dimensions of the Kashmir basin are 185 km (length) and 120 km (width). Only outlet for the drainage system is Baramulla-gorge, where the Jhelum River exits the Kashmir basin. The bordering transverse tributaries flowing across the Pir Panjal and Zanskar ranges have brought enormous amount of fan deposits consisting of boulders, sand and silt over extensive areas at their confluence. The tributaries of Jhelum River are also responsible for changing the shape of the landform through degradation and aggradations processes.

The basin has diverse geological record ranging from Precambrian to Recent (Middlemiss, 1911; Wadia 1975; Raza et al., 1978; Bhatt, 1989). With Salkhala series (Precambrian) and Dogra slates (lower Cambrian) as oldest stratigraphic basement floor (Wadia, 1975; Krishnan, 1982), the basin has a more or less full sequence of fossiliferous Paleozoic such as Panjal Volcanic series (Panjal trap and Agglomeratic slate), gneissose granite, Gondwana shale, Fenestella shale, Syringothyris limestone, Permo - Triassic rocks, conglomerate beds, and varved clays in various parts of Kashmir (Lydekker, 1883, Middlemiss, 1910; Wadia, 1975; Krishnan, 1982). The exposed bedrock units of the valley consist of Panjal Volcanic series (Panjal trap and Agglomeratic slate), gneiss or gneissose granite and metamorphic schists, and Triassic limestone.
Geomorphological Evolution Kashmir Himalaya
Kashmir Himalaya has youngest mountain range possessing a dramatic landscape with snow, glaciers surging river system spreading between the Pirpanjal and the Zanskar and establishment of Indus water shed (Jehlum-Suru Zanskar). The Orogen is marked by two tectonic episodes. The first episode is related to collision between India and Asia that resulted crustal shortening, thickening and initiation of metamorphic impact on sedimentary series of Indian continental margin. The second episode lead to extensional tectonic structure related to exhumation of high-grade metamorphic rock of High Himalayan Crystalline that lead to compression of beds due to ductile normal shearing, doming and normal faulting. The geological events go back to 60 Million years to attain its present elevation and since 15 Million years has lead to initiation and establishment of monsoon system in the region. Pleistocene has been the time period when pulsating uplifts resulted in pushing Himalaya further up causing precipitation in the form of snow around the year giving rise to large glaciers (Valdiya, 1993). Cold conditions were set in Kashmir Himalaya and its adjoining valleys as early as 2.5 million years ago. The glacial period was followed by time de-glaciation that resulted in formation of huge lakes, this period was followed by extreme dry condition when fierce dry wind blew Kashmir valley (Pant et al.1978). The temperature of ice plays major role in movement and morphological activity resulting in staggering geomorphological diversity, exceptionally rich field for study of glacial, fluvial and arid cold landscapes.
B. Description of the Field Sites

During this program participants would have an overview of the general geomorphic setup of the major landforms of Kashmir and Karakorum Himalaya particularly with regard to the landform characteristics of beautiful Kashmir Valley and Drass valley (Ladakh) enclosed by Pir Panjal and Zanskar ranges. These youngest mountain ranges have dramatic landscape with snow, glaciers and surging river system of Jhelum, Sind and deposition rim land along the basin floor produced by hill slope process. The landscape presents wide range of changes in land form due to forces related geomorphic environment related to cold climate, humid climate and dry climate geomorphology related to different processes and their landforms association with Glacial, Fluvial, and Aeolian actions, that are available at every new step; however, during this program following geomorphic sites have been selected to observe them in context of process geomorphology.

DAY 1: FROM SRINAGAR TO MACHOI GLACIER (120 km)

Spot 1: Sonamarg

Sonamarg meaning ‘golden meadow’ is an alpine valley that evolved from glacial action. Sonamarg is situated at an altitude of 2800 m, ~87 km northeast of Srinagar. Sonamarg representing one of the preferred tourist destinations remains inaccessible during winters due to heavy snowfall and is usually open for visitors in late April. The drive to Sonamarg is through the spectacular facets, deep rock-cut gorges, grassy meadows, and forested slopes along the banks of River Sind. The river originating below the lofty peaks near Zojila (3256m) and joined by number of other head streams from Amaranth (5003m), Kolahoi (5425m) and Panjtarni snow fields, flows throw Sonamarg. Sonamarg also serves as a base camp for major tourist routes leading to several mountain lakes, e.g., Vishansar, Kishansar, Gadsar, Satsar and Gangabal, including holy cave of Amarnath for religious pilgrimage. It is also the take off point for a drive to Ladakh across Zojila, a major pass in the Great Himalayan Range, through which the Srinagar-Leh Road passes. Sind basin in general and Sonamarg in particular is an appropriate area to observe the last glacial remnants. Dainelli in 1922 made detailed observations on the glacial sequences in the Sind valley and recognized four glaciations:

(a) First interglacial: the cemented conglomerate of Malshahibagh rests on the glacially molded hill slope and underlies the Karewa clays laid down as the Karewa lake began to form.
(b) Second glacial: the fluvio-glacial deposits and glacial trough below Gund are given in evidence.

(c) Second interglacial: it was suggested that the upper Karewa clays were laid down in the lower Sind.

(d) Third glacial: the striations, roches moutonnees, glacially scooped floor and moraine deposits at Gund in the Sind valley.

(e) Third interglacial: it was not discussed

(f) Fourth glacial: the upper Sind was covered with ice and the while Sonamarg, producing moraines there. Dainelli (1922) also noted two terraces in the Sonamarg, which he correlated with fourth glaciations.

However, De Terra and Patterson (1939) have disagreed with the lower glacially molded hill of Malshahibagh interglacial unit of Dainelli (1922). De terra and Paterson (1939), on the basis of general physiography divided the whole Sind into three parts:

1. The lower Sind is a mature pre-Pleistocene form, extending from the outlet to a point near Hari and carrying the evidences of oldest glaciations only. The region has large and thick deposits of outwash and of lake clays.

2. The middle Sind extends from the Hari to the natural boundary formed by Gagangiyer gorge. The third glacial advance alone has produced moraines and evidence for earlier glaciations lies well above the present valley floor, truncated by erosion into a rising block at Hari.

3. The upper Sind carries the moraines of the fourth and later ice advances above Gagangiyer gorge, which can be divided into the Sonamarg meadow and the Baltal valley.

**Spot 2: After breakfast whole day tour on the Thajwas glacier**

Thajwas is an ideal and easily accessible spot to understand large scale glacial retreat and preserved features. Thajwas Glacier is located about 7 Km from the Sonamarg valley. The adjoining area remains permanently covered with snow throughout the year. Several small streams are gushing out from the Thajwas Glacier to join Sind via Sonamarg. Thajwas Glacier occupied about 2.99 Km² in 1962 and has reduced to mere 1.07 Km² in 2001, which indicates that the glacier has lost 1.92 Km² (~63%) of its aerial extent within the span of 40 years. The drastic retreat of the Thajwas Glacier can be attributed to the prevailing climatic variability. During the last four decades of 20th century, mean maximum temperature has increased by 0.4°C while as the mean minimum temperature has registered an increase of 0.1°C.
DAY 2: FROM SONMARG TO MACHOI GLACIER (30 km)
Spot 1: Machoi Glacier

Machoi is a small transverse valley glacier housed in Kanipathar ranges located SE of Zojila that separates it from westerly Sind Valley. It is 4.19km long and 1.5km to 3 km wide has been named after the highest peak (Machoi Peak ~5458m amsl) that lies at the eastern end of the glacier. Baltal and Zojila are two important points on the 30 km road stretch from Sonamarg to Machoi; the former represents the base station of Hindu pilgrimage to Amarnath Cave, while as later one Zoji-La pass is a gateway to Drass-Ladakh situated on National Highway 1-a road, connecting Srinagar to Kargil and Leh. The Srinagar-Kargil road remains closed to vehicular traffic during winter season due to closure of Zojila pass as result of heavy snowfall. The valley has a distinct climatic characteristic due to its location in the shadow zone of Great Himalaya having an aerodynamic link with the air mass of westerly air flow and westerly disturbances (originating from Mediterranean and Caspian ocean) moving aloft the Pamir Range giving rise to cold anticyclone leading to production of thermal gradient during winter season (October to May) that is responsible for anchoring southerly jet. The study region has cold sub arid type of climate. The winters are long chilly (mean minimum temperature −15˚C to −25˚C), lasting November to May. Summers are short (June to September) mild (temperature varies between −8˚C to 25˚C). Nearly 72% of its annual precipitation is received by Western Disturbances that is confined to November to May which sometimes prolongs to summers as well otherwise summers get scanty rains.

Machoi glacier is selected as benchmark glacier in Drass basin, Kargil, Ladakh Himalaya (Karakorum) been monitored and studied by many geologists/glaciologists in the past 130 years (Lawrence 1895 ; Oldham1895 ;La Touche 1910;Raina 1975; Koul et al 2016).The glacier has experienced a marginal change in glacier extension and volume. The glacier is about one kilometer from the road head, has evidently extended almost down to where road now runs and is shown by heaps of moraines material. The research team of university of Jammu extensively monitored the glacier from the snout(4350m) to the altitude of 4800 m (accumulation zone) by GPS survey and carried continuous field mass balance measurements during 2011 to 2014. The glacier has a positive net balance with cumulative specific balance of 0.16 m w.e./km/yr. This has resulted in shifting ELA from 4540 m asl in the year 2011-2012 to 4509 m asl 2013-2014 (Table 5) and the glacier snout to advance 4 meters in central part (3656 m to 3652 m), but along the sides there has been deformation squeezing and retreat (0.56 m).

The climatic data of Drass reveals that there has been a small increase in annual mean temperature at Drass of −0.426˚C per decade prior to year 1995. However, since 1996
the rate of increase has accelerated to 0.375°C per decade. The analysis of mean monthly temperature (Maximum and Minimum) trend line for period 28 years was lack of fit of lower portion of data (1988-2000) to upper portion of data (2001-2013); hence it is attributed to phase transition threshold. It indicates that winter is cooler, late winter warm humid, and summer cool and wet during time series 2001-2013 in comparison to cold winters (November-March), mild late winter (March-May) and warm and dry summer during 1988-2000. Further, the decrease in mean maximum as well mean minimum temperature during 2004-2013 is associated with change with inter-decadently of Pacific Oscillation and with increase in El Nino/southern Oscillation events that resulted in lower ablation season temperature particularly during summers of 2004-2014 (Yasunari, 1987). These trends in weather conditions have undoubtedly leaded a favorable environment for decelerated retreat to the extent of no change in glacier area to slow retreat of glacier snout and marginal loss in Machoi glacier area.

Fig. 4.
Location map of Drass glacier sub-basin and Machoi Glacier, Kargil Ladakh (after Koul et al., 2016).
DAY 3: FROM SRINAGAR TO WULAR LAKE (50 km)
Spot 1: Wular Lake

Wular Lake is located in northeastern corner of Kashmir basin at a distance of ~50Km from Srinagar. Wular is the largest freshwater lake in India spread over an area of 189 km² with extensive marshes of emergent and floating vegetation. In view of tremendous ecological and economic importance, the lake has been declared as Ramsar site in the year 1990 (no. 461). The area around Wular lake comprises of a range of geological Formations such as Permian, Panjal trap, Agglomeratic slate, gneiss or gneissose granite and metamorphic schists, upper and lower Triassic limestone and Slate with scanty intercalations of black Shale as hard rock units and recent Alluvium and; however, the area is dominated by the upper Palaeozoic and Triassic rocks (Middlemiss and Bion, 1910; Thakur and Rawat, 1992). The upper Palaeozoic rocks (Agglomeratic slates, Panjal Traps, slates and granites), overlain by Triassic limestone series (blue and dolomitic limestone), cover the maximum area from NE side of Wular lake. At some places the Triassic rocks are overlain by recent sediments. Compared to hard rock terrain, Recent Alluvium covers a small portion of the Wular lake surroundings, which comprises of pebbles, sand silt and clay.

Wular acts as a storage sump for whole drainage of the Kashmir basin; however, with continuing inflow of the sediment load and solid waste the maximum depth of lake has reduced to 7 meters from 20 meters in 18th century. Moreover, state of human interference, in the form of settlement expansion around the lake, farming practices and encroachment has resulted in degradation of the ecologically sensitive aquatic ecosystem (Fig. 5). This site provides an opportunity to witness transformation of natural landscape and alteration of aquatic system because of natural and anthropogenic reasons over time.

*Fig. 5.*
East to west view of the Wular Lake.
DAY 4: FROM SRINAGAR TO HIRPUR (SHOPIAN) (60 km)
Spot 1: Hirpur (Shopian)

The site has been selected to observe one of the most remarkable geomorphic features of Kashmir valley, i.e., Karewa (Plio-Pleistocene) deposits. Karewa is fluvio-glacial and lacustrine sediments, which has been assigned Group status (De terra and Paterson, 1939; Farooqi and Desai 1974; Bhatt 1989) (Fig. 6; Table 1). These deposits spread in the form of mounds, terraces, flat lands, dissected plateaus, and pop-ups from Shopian-Kulgam in the south Kashmir through Badgam in the middle and extending to Handwara for a stretch of about 120-130km with varying width from 13-15km (Wadia, 1975). Dominant in SW of the Kashmir basin, the Karewa deposits occupy nearly an area of 2500 km². These deposits consist of 1300m thick sequence of unconsolidated clays, sands, and conglomerates with lignite beds unconformably lying on the bedrock and are overlain by the recent river alluvium (Bhatt 1975, 1976; Wadia 1975; Burbank and Johnson 1982; Singh 1982). The Karewa deposits preserve the record of past four million years in which the sedimentation is controlled by the tectonic events (Burbank and Johnson 1982). The Karewa deposits also containing volcanic ash horizons where some of the ashes from Pir Panjal side were found to be 2.4 ± 0.3 Ma old (Burbank and Johnson, 1982). Based on unconformity (a boulder bed) the Karewa Group has been subdivided into Hirpur and Nagum Formations by Singh (1982); whereas, Bhatt (1989) divided them further into younger Hirpur, Nagum, and Dilpur Formations (Fig. 7). The Hirpur Formation broadly consists of gray to bluish-gray clays, light-gray sandy clays, fine to coarse-grained green to purple sands, conglomerates, lignite, and lignitic clays. The Nagum Formation is made up of fine to coarse-grained greenish to purplish sands, gray and ochre sandy clays, ochre and cream colored marls and gravels, while as the upper Dilpur Formation mostly consists of brown silts.

The southwest Kashmir (Pir Panjal range) hosts significant Karewa deposits, descending through long gentle slope towards the valley floor as compared to short and moderately steep slopes on the northeast Kashmir (Zanskar range). The Karewa deposits are mostly capped by the loess sediments, which is the youngest unit of the Karewa group and are aeolian in origin (Pant et al., 1978; Bronger et al., 1987). These loess sediments are characterized by the presence of inter-bedded profiles of paleosols. The maximum thickness of loess is ~22 m on the southwestern side compared to only ~4 m on the northeastern part of the Kashmir basin. The loess sequence on SW (Pir Panjal) side is superimposed on the gravel bed of the Shopian Member of the upper Karewa. However, from NE (Zanskar) side, these loessic sediments cap the upper Karewa laminated silt of the Pampore Member. The loess deposits along northeastern part are younger than 85 ka years. However, along the southwestern part entire loess sequence is at least ~300 ka old (Singhvi et al., 1987).
The whole lower Karewa unit is exposed along the northeast flowing Pir Panjal tributaries on the southwestern side (Fig. 6).

Fig. 6.
Karewa Formation of Kashmir basin (after Bhatt, 1989).
Table 1: Stratigraphic succession of Karewa Formation (after Wadia, 1975; Bhatt, 1976, 1989).

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<tbody>
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<td>Alluvial deposits</td>
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<td>Loess-paleosol succession of Dilpur Formation</td>
<td>Dilpur Formation</td>
<td>Layers of brown silt vary from calcareous to non-calcareous types</td>
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<td>Shopian Member</td>
<td>Nagum Formation</td>
<td>Gravels, sand, sandy clay, marl and silt</td>
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**Angular unconformity**

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<td>Methawoin Member</td>
<td>Hirpur Formation</td>
<td>Clay, sandy clay, conglomerate, varve sediment, lignite and sand</td>
<td>Pliocene to Pleistocene</td>
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<td>Rambiara Member</td>
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<td>Er.Unconformity</td>
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<tr>
<td>Dubjan Member</td>
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| Unconformity                          |                                                |                                                |                    |

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<td>Triassic Formation</td>
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<td>Andesite, Basalts etc.</td>
<td>Permian</td>
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<tr>
<td>Agglomeratic slate</td>
<td>Slates</td>
<td>Upper carboniferous</td>
</tr>
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</table>
Fig. 7.

(a) Litho-column of Lower Karewa (Hirpur Formation) (after Bhatt, 1989), (b) showing exposure of tilted (NE) lower Karewa at Hirpur village in upper Rambiara valley. Letter A is younger conglomerate marker horizon in Methawoin Member.

Spot 2: Pampore (45 Km)
While returning back from Hirpur the next spot would be the upper Karewa deposits (Pampore Member) named after nearby town Pampore. Although, Pampore Member is invariably and abundantly exposed at different locations in the cliff walls of the numerous Karewa plateau from Anantnag area in the southeast, through Bijbiara, Tral to Pattan and Baramulla area in the northwest Kashmir; however, the Member is best developed and easily accessible in Pampore town, where it is ~ 41m thick (Bhatt, 1989). The Member extends from Pampore in the north to Sambur in the south (Bhatt, 1989). Pampore Member consists of light grey and orche-coloured sandy clay and coarse to fine greenish and purple sand, with thin layers of bluish-grey to cream color clay and marlekor band (Bhatt, 1989). The base of the Pampore Member is not exposed in the type section, whereas the Triassic limestone is exposed in the adjacent parts of the section at Sambur. A characteristic lithological feature of Pampore Member is the sequential occurrence of finely laminated sand-sandy clay alterations, sand and light gray structure-less muds in vertical successions. The sand to sandy-clay alterations often show ripple structures; the sands are usually cross-bedded. The Pampore Member was deposited in a 1-2m deep lake; as a result, the lake bottom was always within the reach of waves and received enough sunlight and supported dense subaqueous vegetation. The deeper facies lack sand layers and mottling by rootlets, suggesting the maximum depth of the lake basin between 5 and 10 m. De terra and Paterson (1939) has recorded an assemblage of Mammalian vertebrate fossils including Elephas hysudricus from the basal part of Pampore Member. Moreover, there is a record of fresh water Ostracodes and Molluscs from the strata of Pampore Member (Bhatia, 1968).
Spot 3: Srinagar
Apart from the longitudinal tectonic belts, existence of transverse lineaments/faults is characteristic feature of Himalayan tectonics. These transverse faults trend oblique to the NW-SE grain of the Himalaya and extend northwards from the alluvial plains through the pediment zone south of foothills of the Tertiary belt into the Lesser Himalaya (Valdiya, 1979). Many of them confirm to the known deep seated ridges beneath the accretionary wedge of Indo gigantic plain (Virdi, 1979; Valdiya, 2002); and behave as wrench or tear faults. Yet little is known about their role in accommodating N-S shortening between India and Eurasia, and in most cases slip rates are only estimated from satellite geodesy and GPS. These transverse lineaments/faults show four prominent trends viz, NNW-SEE, N-S, NNE-SSW, and NE-SW.

Here, we present one of these transverse structural lineaments known as Srinagar-Pathankot Fault 'SPF' (suspected). The journey will be devoted to interpretation of geomorphic features associated with Srinagar-Pathankot Fault 'SPF'. We will explore the different landform assemblages linked to the northern segment of the 'SPF'. Srinagar-Pathankot Fault 'SPF'-one of the transverse lineaments of NW Himalaya which runs N-S across Pir Panjal Range (PPR). This right lateral strike slip starts from Pathankot cutting across Pir Panjal Range (PPR) running through Kashmir basin for a distance of more >150 Km.

We name this fault as Srinagar-Pathankot (SPF) Fault, after the two prominent cities at its northern and southern ends respectively. The 'SPF' consists of two principal fault strands-the Southern strand runs from Pathankot up to Riasi along Sidhra ridge, the axis along which the Chenab River flows. The anticlinal ridge in fact forms a part of the NW-SE Upper Siwalik mountain belt which has shifted from its original position to N-S orientation (Fig. 8).

Fig. 8.
Upper Siwalik mountain belt in Jammu, indicating N-S orientation instead of NW-SE, against general trend of mountains in NW Himalayas.
Here we focus on the northern strand of SPF known as Shopian-Srinagar strand. This right lateral strike slip fault starts from Rambiara wind gap running across the Kashmir basin in N-S direction. Its strike varies and is northerly in the northern segment, north of Kashmir Basin, forcing the axial River Jhelum to make a hairpin bend in its course at Srinagar and dies out up to at least mouth of Sind River.

The Shopian-Srinagar (SS) fault is characterized by geomorphic expression including river offset, shutter ridges, sag ponds, and linear, strike-parallel valleys. The obvious imprint of this S-S strike-slip fault include the first-order, near-fault tectonic landforms at the southern end of Pir Panjal range where mountain ridges initially oriented in NW-SE direction, migrate laterally in conjunction with fault motion in a meridional direction due N-S. Continued slip along S-S fault leads to stream capture of Dodhganga and Shaliganga rivers which route across the Pir Panjal range forcing them to flow in northerly direction along the fault instead of northeast. Further down, the great bend of Srinagar is an excellent offset marker where axial river Jhelum crosses S-S fault thereby, giving rise to platted structural anomaly. East of this S-S fault above the great bend of Srinagar (in the upstream direction) the river Jhelum shows anomalous compressed meanders with high sinuosity index; while as, west of this N-S fault, the river Jhelum is disposed with deflated meanders with relatively low sinuosity index.

This is further corroborated by considering the extension of the fault further north where it marks the elevated part of Srinagar city, which according to archival scribes has been devastated many times by earthquakes. This strip of elevated upper Karewa (Pleistocene deposits) sediments lies between the Dal lake on the east and the Anchar lake on the west, a tectonic situation analogous to separation of Lake Patron from Lake Vegoritis by a narrow strip of land elevated along Vegoritis fault in Ptolemais-Florina basin in NW Macedonia (Diamantopoulos et al., 2014).

**Day 5 - Pahalgam**

Located 95 km from Srinagar at a height of 7200 ft, Pahalgam, known as the “Valley of Shepherds”, is a famous hill station in Jammu & Kashmir. Pahalgam is surrounded by thickly wooded pine forests, breathtaking vistas of meadows and snow-clad Himalayan mountains.

**Day 6 - Departure from Srinagar to Delhi**
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A2: Geomorphological Field Guide Book on LATERITES and BACKWATERS of KERALA

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of the International Association of Geomorphologists (IAG),
New Delhi (6-11 November, 2017)

Citation:
on Laterites and Backwaters of Kerala (Edited by Amal Kar).
Indian Institute of Geomorphologists, Allahabad.
Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
## Itinerary

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Places from - to</th>
<th>Stay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>31 October 2017</td>
<td>New Delhi to Thiruvananthapuram by Flight; Briefing and discussion</td>
<td>Thiruvananthapuram</td>
</tr>
<tr>
<td>Day 2</td>
<td>01 November 2017</td>
<td>Thiruvananthapuram to Poonmadi &amp; back Field visit to Vizhinjum, Kovalam, Nedumangad, Kallar and Poonmudi</td>
<td>Thiruvananthapuram</td>
</tr>
<tr>
<td>Day 3</td>
<td>02 November 2017</td>
<td>Thiruvananthapuram to Kumarakom Field visit to Varkala, Kollam, Asthamudi Lake, Chavara, Thottapally, Alappuzha</td>
<td>Kumarakom</td>
</tr>
<tr>
<td>Day 4</td>
<td>03 November 2017</td>
<td>Kumarakom to Kozhikode Field visit to Thannermukkom Barrage, Muzaris, Angadipuram</td>
<td>Kozhikode</td>
</tr>
<tr>
<td>Day 5</td>
<td>04 November 2017</td>
<td>Kozhikode to Mangalore Field visit to Kannur, Taliparamba, Bekal Fort, Kasargod</td>
<td>Mangalore</td>
</tr>
<tr>
<td>Day 6</td>
<td>05 November 2017</td>
<td>Mangalore to New Delhi by Flight</td>
<td>New Delhi</td>
</tr>
</tbody>
</table>
Located in the southwestern corner of Indian peninsula, and sandwiched between the Lakshadweep sea in the west and the Western Ghats in the east, the State of Kerala covers an area of 38,860 km² and accommodates, as per 2015 estimate, about 35 million people (Fig. 2 and 3).

The state is a type locality of laterites, and houses the largest backwater (lagoon/estuary) system in the west coast of India. To appreciate these and other related landforms of Kerala, the tour proposes to traverse the length and breadth of the state, including a west to east transect from the sea coast to the summit of the Western Ghat and a longitudinal transect from the southern end of the state to its northern extreme. Before describing the sites to be visited we first provide a brief introduction of Kerala, highlighting some of its salient geomorphic features and other important aspects.
Weather and Climate

Climatically, Kerala comes under the tropical monsoon belt. Orographic control on climate is well evident in the pattern and distribution of rainfall and other weather parameters. Normal annual rainfall in Kerala is about 280 cm. Precipitation shows increasing trend from the coast to the inland, and the maximum is recorded along the foothills around Neriamangalam (451 cm) in the south and Kuttiyadi (417 cm) in the north. From there the rainfall decreases eastward, and the lowest rainfall (<100 cm) is recorded in the rain-shadow region sloping towards the Tamil Nadu plain. Based on rainfall and cloud characteristics four seasons can be identified in Kerala. These are: South West monsoon, locally known as Kalavarsham (June-September), North East monsoon, locally known as Thulavarsham (October-November), Winter (December-February) and Pre-monsoon (March-May). About 75% of the total rainfall precipitates during the SW and the NE monsoons. Rainfall increases steadily from south to north. Kerala receives rainfall almost in every month (Table 1). This year-round rainfall and high precipitation in the foothills have contributed to the perennial nature of the Kerala rivers. Recent studies suggest that the foothill region in south Kerala now experiences 15-20% reduction in annual rainfall, which may affect the hydrology of the State.

Average temperature in Kerala varies roughly between 27°C and 32°C. The period from March to May is the hottest when temperature reaches the maximum (>32°C). From June, it gradually comes down due to heavy monsoon rain. An increasing trend is noticed again in the months of October and November, followed by lower temperatures (<27°C) in December and January. The stations located near the coast are influenced by land and sea breezes, and the seasonal and diurnal variations of temperature are not so high (Table 1). However, in the high hill ranges, which are typically sub-tropical, temperature comes down to <16°C, and at some places the diurnal variation is very high (>15°C) in some months. This is a typical example of a par-humid area where the tropical climate has been remarkably modified due to higher altitude.
Table 1: Monthly distribution of rainfall and temperature at Kochi (2000-2012)

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>January</td>
<td>32.3</td>
<td>32</td>
</tr>
<tr>
<td>February</td>
<td>24.3</td>
<td>32</td>
</tr>
<tr>
<td>March</td>
<td>39.1</td>
<td>32</td>
</tr>
<tr>
<td>April</td>
<td>103.7</td>
<td>33</td>
</tr>
<tr>
<td>May</td>
<td>270.8</td>
<td>32</td>
</tr>
<tr>
<td>June</td>
<td>615.9</td>
<td>30</td>
</tr>
<tr>
<td>July</td>
<td>516.1</td>
<td>29</td>
</tr>
<tr>
<td>August</td>
<td>330.5</td>
<td>30</td>
</tr>
<tr>
<td>September</td>
<td>283.8</td>
<td>30</td>
</tr>
<tr>
<td>October</td>
<td>422.1</td>
<td>30</td>
</tr>
<tr>
<td>November</td>
<td>135.0</td>
<td>31</td>
</tr>
<tr>
<td>December</td>
<td>40.4</td>
<td>32</td>
</tr>
</tbody>
</table>

Geomorphology

Relief

Relief distribution in Kerala is asymmetric. As much as 62% of the total geographical area is below 100 m (Chattopadhyay and Mahamaya, 1995). The coastal plain is wide in the central part, especially around Vembanad Lake where it coincides with a sedimentary basin, and tapers both towards north and south (Fig. 4).

Fig. 4. SRTM Digital elevation model of Kerala (source: Chattopadhyay and Suresh Kumar, 2012)
From the coastal plain, elevation increases in a stepped manner, justifying the nomenclature of 'Ghats'. The average rise of land is 27 m for every kilometre from the coastline towards east and the relief amplitude increases with the rise in altitude. Seventy per cent of landmass in Kerala fall in the slope category of >15% (Chattopadhyay and Mahamaya, 1995). The crest line of the Western Ghats reaches the maximum altitude of 2695 m at Anamudi, which is the highest point in south India. The monolithic Western Ghats is broken by the 30 km wide Palghat Gap at the altitudinal level of 100 to 200 m. This Gap connects Kerala plains with the Tamil Nadu plains, and has pronounced influence on the climate, culture and economy of the State. The Western Ghats and the Eastern Ghats merge at the Nilgiri Hills in Tamil Nadu, an extension of which is the Kunda Hill ranges in Kerala. About 23% of the land lying above 600 m altitude is the source area for all the rivers in the State and is the primary source zone for sediment and water. Abrupt rise of the Western Ghats from 100 m upward with precipitous slope is a characteristic feature of Kerala's topography that controls hydrology, climate, land use, infrastructural development and settlement distribution.

**Geology, Lineaments and Landforms**

Geologically Kerala is a part of the south Indian shield. The rock types are dominated by crystalline formations. Four major geological formations found in Kerala are: (i) Crystalline rocks of Precambrian, (ii) Sedimentary rocks of Tertiary, (iii) Laterites capping the crystalline and the sedimentary formations, and (iv) Recent and sub-recent sediments forming the low-lying areas, coastal area and river valleys (Geological Survey of India, 2005). Bulk of the rocks of Kerala, especially the granulites and associated gneisses, belong to the Precambrian. The on-land sedimentary formations are confined to Neogene period only (Soman, 2002). They include pebble beds, sandstone, grit, clay with shales, marl and limestone. All the rock types (crystalline and sedimentary) are lateritised to variable depths. Duricrust formation is well-marked at places. Recent and sub-recent sediments cover the low-lying areas, coastal plains and river valleys. Rock types, their composition and degree of weathering influence the landform development. Rugged terrains are mostly on hard rocks and radial drainages usually characterize the areas affected by granite intrusions. Structural control is well evident in drainage development. Fractured hard rocks are conducive for groundwater recharge. Laterites are also good aquifers.

Lineaments in Kerala are oriented in the directions of NW-SE, WNW-ESE, NNW-SSE, N-S, NE-SW and E-W (Katz, 1978; Varadarajan and Balakrishnan, 1980). The NE-SW lineaments are probably the youngest (Nair, 1990). Changes in sea level, river courses and foundering of river mouths are noted in various parts of the state. Raised river terraces, pebble beds and abrupt changes in river direction found in the Palghat Gap might have resulted from tectonic movements (Rajendran and Rajendran, 1996).
Almost all the rivers in Kerala are structurally controlled, as is evident from the straight courses of most of the rivers (Fig. 5).

Landform zones, running parallel to the coastline in NW-SE direction, follow the longitudinal trend of topographic grain of the State. Three well-identifiable landform zones with distinct geomorphic processes are: the Western Ghats, the Coastal Plain and the Undulating Lateritic Terrain (ULT) connecting these two units (Fig. 6). The ULT is primarily a subdued terrain, evolved through pedimentation, lateritisation and parallel slope retreat, valley formation and expansion of aggradational plain. The Western Ghats, occupying the eastern part of the State, form southern segment of the 'Sahyadri' or the Great Indian Escarpment. Origin of the Western Ghat scarp is yet to be fully understood. Reviewing available literatures, Dikshit (1981) suggested three hypotheses, namely, (i) fault scarp hypothesis, (ii) erosional escarpment hypothesis, and (iii) hypothesis of a dead cliff. Based on geological, geomorphological and geophysical evidence Radhakrishna (2001) opined that the Western Ghats represent the edge of an up-raised and disrupted continental block formed during
the early Miocene. The upliftment of the Western Ghats is linked with the west coast faulting, which is not a single fault; rather it is a composite unit of several sections separated from each other by horizontal shears (Balakrishnan, 2001). Landscape development in the fringe of Western Ghats is associated with scarp retreat along the structurally weaker planes like lineaments, fractures, foliations, etc. Analysis of valley configuration, particularly the valley wall, indicates topographic rejuvenation, valley incision and scarp retreat along the headwaters. In fact, scarp retreat is considered to be a principal mechanism leading to the development of the Western Ghats.

The Palghat Gap at an altitudinal range of 100 to 300 m, drained by Bharathapuzha River, is a major break within the Western Ghats ranges. Two prominent tectonic blocks of Wayanad and Anamalai are located in the northern and southern segments of Palghat Gap, respectively. The prominent Western Ghats scarp faces are associated with these two tectonic blocks in the altitudinal range of 600-900m. In the absence of any major fault onshore the Western Ghats scarp recession can be measured from the west coast fault (Gunnell and Radhakrishna, 2001 and Balakrishnan, 2001). At 845°N latitude the Western Ghats scarp (600 m altitude) is at a distance of 45-50 km from the coastline. This distance is an approximate measurement of scarp retreat. Keeping aside the Vembanad sector, which is a depositional emergent coast, the retreat value in Kerala segment (Malabar Coast) is in the order of about 40 to 45 km on an average, which is comparable to the value of 40 km worked out by Balakrishnan (2001) for the segment from Goa to Narmada in the Konkon coast.

The north-easterly tilted Wayanad plateau, drained by Kabini River, is well developed at an altitudinal range of 700 to 900 m. It is characterized by a subdued relief and wide valleys. The high altitudinal zone extends further south to Kunda Hills, Silent Valley and Attapadi Valley adjoining the Nilgiris where the Eastern Ghats merges with the Western Ghats to the northeast of the Palghat Gap. The part of the Western Ghats extending from south of the Palghat Gap to Trivandrum-Nagercoil is considered as the Southern Ghat or the southern Sahyadri. Width of the Western Ghats narrows down in the Khondalite belt to the south of Achankovil-Kallada shear zone. The Agasthamalai (1809m) is the highest point in this part and the crest line slopes towards north. There are two high level surfaces above the Western Ghats scarps, marked in six patches and three low-level surfaces between the coast and the 300 m altitude (Table 2; Chattopadhyay, 2004). Western Ghats, as the catchment area of all the rivers of Kerala, plays a very important ecological, economic and cultural role.
Table 2: Classification of planation surfaces in Kerala and their occurrence

<table>
<thead>
<tr>
<th>Level</th>
<th>Sub-level</th>
<th>Probable* geological age</th>
<th>Altitude range (m)</th>
<th>Surface identified at</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Level Planation Surface (HLPS)</td>
<td>I</td>
<td>Early cretaceous</td>
<td>&gt;2400</td>
<td>Anaimalai</td>
<td>Residual hill Anaimudi (2695m) highest peak in south India</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>Ecocene</td>
<td>1500-2000</td>
<td>Munnar plateau</td>
<td>Well developed, long slope, grassland topography</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>Miocene</td>
<td>700-1000</td>
<td>Wayanad plateau</td>
<td>Easterly sloping, extension of Mysore/Karnataka plateau, most bevelled surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bhavani tract</td>
<td>Easterly sloping narrow ridge like area, north of Palghat gap</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nelliampathi plateau</td>
<td>Located south of Palghat gap, south westerly sloping, comparatively dissected</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Greater Periyar plateau</td>
<td>Extensive, marked in two levels, Peermade plateau included</td>
</tr>
<tr>
<td>Low Level Planation Surface (LLPS)</td>
<td>I</td>
<td>Mio-Pliocene</td>
<td>100-300</td>
<td>Palghat Gap</td>
<td>Structural-erosional surface</td>
</tr>
<tr>
<td></td>
<td>II</td>
<td>Pleistocene</td>
<td>40-230</td>
<td>Lateritic plateau</td>
<td>Widely developed in north Kerala, characterised by duricrust formation</td>
</tr>
<tr>
<td></td>
<td>III</td>
<td>Recent</td>
<td>0-50 m</td>
<td>Alluvial plain, valleys and coastal plain</td>
<td>Found throughout the State, some parts of coastal plain lateritised, hard crust formation also evident in coast (Kannur town)</td>
</tr>
</tbody>
</table>

The steep-sloping land, a predominance of lateritisation, the narrow width and structural control on drainage pattern and the topography have, together, imposed certain restrictions on the development of fluvial landscape. Flat-bottomed valleys, flanked by moderate to steep side-slopes, are important geomorphic features in the midlands and the highlands of Kerala. These valleys owe their origin partly to slope wash and scarp retreat than to normal fluvial action. However, majority of the valleys/ floodplains are found to be misfit. In other words, rivers are flowing through a valley, which is much wider and possibly not carved out by the present river system.

Valleys and floodplains in most cases are narrow, with possible exception of the Bharathapuzha River, the Periyar River and the Pamba River. Bharathapuzha River has the largest catchment area within Kerala, and exhibits well-developed fluvial terraces, preserved along the tributary valleys. Paired terraces found along the tributaries indicate their recent origin. This river has well-developed floodplain along its lower courses. The Periyar is the longest river in Kerala. Major part of its course flows through a metamorphic terrain and exhibits good structural control. The river's course is aligned at places with the major fracture lines (Mahamaya, 2007). Its lower course, extending over a distance of about 30 km, exhibits wide flood plains composed of various fluvial units like levee, back-swamp, meander scar, braided bar and point bar. There are meander scars or palaeo-meanders in the lowlands, indicating shifting of river courses. Landform in Kerala has evolved through successive evolutionary stages, resulting in relict summits at various levels. The denudational slopes around first-, second- and third-order summit areas are narrower than the fourth-order summit areas, which indicate levelling of terrain with advancement of stages and processes (Mahamaya, 1998).

The lowlands are characterized by river deposits, lacustrine deposits, wetlands and relict landforms in patches. An inland delta has developed in the southern fringe of the Vembanadlake, drained by the Pamba-Manimala-Achankovil river system. Similar deltaic landscape can also be found at the confluence of the Muvattupuzha, and the Periyar with the Vembanadlake. Characteristics of sea waves, tidal range and direction of littoral current are the main factors influencing the coastal processes. In addition to these, the rivers directly debouching into the sea have pronounced influence on coastal geomorphology, sediment distribution and beach character. Formation of offshore bar and subsequent development of lagoon due to sea level change is a unique feature of Kerala coast. The coastal zone in Kerala is not uniform; it exhibits distinct spatial differences in material composition, morphology and surface features from north to south.

The central part of the coast from the Ponnani River mouth to the north of Asthamudi is composed of recent sediments, and is considered as a permeable coast. Existence
of an internal basin covering this area since Tertiary has been reported (Chattopadhyay, 2002). The northern and southern parts of the coast are characterized by laterites, sedimentary deposits and crystalline hard rocks. The southern part of the coast is characterized by Varkala cliff on sedimentary rocks, Kovalam headland on the crystalline and the Teri Sand deposits further south. Pocket beaches are well developed. Palaeo-sand ridges are found in patches in different parts of the coastal plain. Around 250 km of Kerala coast is affected by severe erosion.

**Laterite**

Kerala is a type locality of laterite. Nearly 60% of the geographical area of the State is covered by laterite or laterite-derived materials. From the coast to the foothills, lateritisation process dominates the landform development. Remnants of laterites, including hard crusts, are found at higher altitudes, which suggest uplift of the landmass. Laterites, the products of chemical weathering, are unique features in the tropical countries. The principal geological mechanism involved in laterite formation is horizontal and vertical movement of water in a near-peneplaned surface and chemical alteration of the parent rocks. Strong and deep weathering is an essential factor in initiating planation process in humid tropics with chemical down-wearing of the regolith as clays are removed from the surface by rain-wash and also subterraneously, particularly in the low-relief areas (Verstappen, 1987). Laterite usually forms during the final stage of land surface reduction and provides a cap rock protection to the old surface. It has developed on all types of rocks, including the recent sediments, and is found both in detrital and residual forms. Detrital laterite is found in the river valleys along the slopes of both lateritic and non-lateritic hillocks, where it is transported, deposited and reconsolidated. Occurrence of detrital laterite as cap of the isolated hillocks signifies topographic inversion (Karunakaran and Sinha Roy, 1981). Lower part of the detrital laterite deposits is found to be welded to the top part of residual laterite components. The top part of the detrital laterite is pedogenic, where the concentration of iron is controlled both by soil forming processes and contribution from upland laterites through denudation. Duricrust formations facilitate parallel slope retreat or pediplanation in tropical areas; however, in the absence of a crust, landform usually develops due to peneplanation. Lateritic mesas at different altitudinal levels below 250 m are conspicuous landform features in Kerala. Whether these surfaces are products of different erosion cycles and belong to different ages, or whether they are part of the differentially eroded single planation surface, is still being debated. Similar surfaces have been reported from other tropical areas like Uganda. McFarlane (1981) is of the opinion that altitudinal differences may be a part of denudational process and need not necessarily be due to different erosional cycles. Development of laterite profile is linked with polycyclic geomorphic surfaces developed at various levels in Kerala.
Backwaters

Backwaters in Kerala is a network of 1500 km of canals, both man-made and natural, linking 38 rivers and five big lakes/lagoons/estuaries, extending from one end of the State to the other. As wetlands they present a dynamic ecosystem having complex interrelationship of soil, hydrology and vegetation, and occupy the transitional zone between the aquatic and the terrestrial environments, sharing the characteristics of both. They provide fish, hold excess monsoon runoff, facilitate water percolation, purify water, maintain the nutrient cycle, provide sites for biodiversity, easy inland water transport, retting of coconut husk, and absorb pollutants. As most of Kerala's rivers pass through the backwater system before emptying into the Lakshadweep Sea, the backwaters tend to be enriched with nutrients brought down by the rivers. The sediment and nutrient loads flowing down with the river water first settle (or is naturally panned) in the backwaters before they move to the sea. As a result, the productivity of the coastal waters is linked to the nature of the settling process in the backwaters. The presence of the backwater system in the coastal plain has added to the diversity of the resource base of the state. It created an additional opportunity for the fishermen and to have a choice other than the sea for fishing activity. Backwaters excluding the canals are found either as coast-parallel or coast-perpendicular in their plan form. The coast-parallel backwaters have developed due to transgression/regression activities liked with sea level change and surrounded by recent sediments, whereas coast-perpendicular water bodies are mostly foundered river mouths and are surrounded by laterite landscape.

Socio-economic Aspect

Kerala is perceptibly different from the rest of the States in India and is globally known for its significant achievement in human development. Utterance of the word Kerala brings the image of dense coconut groves skirting the blue water bodies and sea waves to a beholder (Fig. 7 and 8). It evokes different meaning to different people. We record some of the perceptions here. Traditionally Kerala is well known for spice trade. The Arabian and the European traders considered Kerala as the 'Land of Black Pepper'. For the climatologists, Kerala is the gateway to southwest monsoon for mainland India, and a State soaked by two monsoons. Agricultural scientists consider Kerala as the land of plantations, particularly spices and rubber. Social scientists feel excited about Kerala for having the first democratically elected Left Government during the first election in 1957 itself; continuous top position among all the states in India in matters of human development index and other demographic characteristics; recipient of the highest foreign remittance through its residents abroad; and a land of immigration and emigration. To the earth scientists, Kerala is a type locality of laterite.
According to the 2011 Census, Kerala had a population of 33.4 million in 38852 sq. km area, which translates into 2.76% of India's total population living in 1.23% of the country's area. The population density is 859 per sq. km, and a sex ratio of 1084 females per 1000 males. The decadal growth rate of population is 4.86. The literacy percentage in the state is 93.9%, where the male literacy is 96% and female literacy 92%, all the figures being the highest in India. Kerala is one of the most urbanised states in India. Thiruvananthapuram (erstwhile Trivandrum), the capital city of Kerala, has a population of 1.69 million.

A staggering total of 525 towns and cities occur here, accommodating about 48% of the total population in the cities, the rest living in the rural areas. Thiruvananthapuram accounts for 5.0% of the total urban population, followed by Kochi (erstwhile Cochin; 4.0%), Kozhicode (erstwhile Calicut; 3.5%), Kollam (2.3%) and Alappuzha (1.5%).

Welcome to Kerala, 'God's Own Country', as the Department of Tourism, Government of Kerala proclaims; explore this part of India through a short but intensive field trip and enjoy Nature's bounty.
Day 1: 31/10/2017  
New Delhi to Thiruvananthapuram by Flight  
Stay at Thiruvananthapuram.

The first day will be spent on briefing on the general characteristics of Kerala State, and on the field sites. We propose four transects to cover the entire state. One transect is from west to east and the rest three are south to north. All parts of Kerala are well connected through road network, although road density is higher in the coastal plain and midlands, as compared to the hilly Western Ghats (Fig. 9). The tour is intended to provide a comprehensive idea about Kerala’s terrain, including its landform, land use, settlement pattern and people.

Day 2: 01/11/2017  
Transect I: Thiruvananthapuram to Vizhinjum, Kovalam, Kallar, Poonmadi & back  
Stay at Thiruvananthapuram.

The Transect-I from Trivandrum to Poonmudi traverses all the three physiographic zones in the southern part of Kerala. Geologically, this segment forms part of the Kerala Khondalite belt (KKB). The boundary between the Khondalite (garnet-sillimanite metapelites) and the Charnockite massif in south Kerala is along the Achankovil River which follows a lineament similar in straightness and geometry to the Proterozoic shear belts further north in Tamil Nadu and Kerala (Hansen et. al., 1987). The day will be spent in exploring the low undulating terrain, cut across the lateritic midlands and foothills, and finally reach the Western Ghat crest at Ponmudi. The change in landform from the coast to the mountain and consequent change in land use and settlement pattern will be evident through this trip.

Stop 1: Vizhinjam-Kovalam

Vizhinjam, a fishing village surrounding a natural port, is now being developed as an international sea port. The notable geomorphic features are irregular coast with exposed rocks, sea cliffs, promontories, and pocket beaches. Kovalam, located to the north of Vizhinjam is a globally known tourist spot in Kerala. The Kovalam headland is composed of crystalline rocks. This promontory divides the Kovalam coast into two halves. The Kovalam beach is erosional and has undergone modifications in recent years. Remnants of marine terraces are also evident. There are Teri Sand deposits and Tertiary cliff towards the south of Vizhinjam.
Fig. 9.
Transport network in Kerala.
Stop 2: Nedumangad
The next stop at Nedumangad is through Thiruvananthapuram city. Nedumangad is a small municipal town located at the outskirt of Thiruvananthapuram city to the north and forms part of the Thiruvananthapuram Metropolitan Area. There is a structural hill passing through this town. Undulating lateritic terrain with intervening narrow alluvial valleys characterize the landscape in this area. The road follows the river valley, winding through elevated lateritic ridges. Altitude of the area is around 68 m. Nedumangad is one of the towns in the chain of foothill-towns developed throughout Kerala to facilitate marketing of hill products. Rubber and pepper plantation dominate the land use. There is an international vegetable market in this town. Natural landscape has been intensively altered through construction of settlements and terracing to accommodate plantations. Valleys are filled up with lateritic soils, thus altering the local hydrological condition.

Stop 3: Kallar
The road moves towards north east along the valleys cutting across undulating terrain. The next stop is beside the Kallar River, a tributary of the Vamanapuram River, and near a small town named Kallar in the foothills. The river bed is full of rounded boulders and pebbles (Fig. 10). In fact the name of the river is derived from Kallu (stone in Malayalam language) and Ar (river in Malayalam language). The river loses much of its velocity due to sudden drop in slope from the Western Ghats to the foothill. As a result large boulders, bearing evidence of river erosion, are deposited in the river bed. This river experiences flash flood with sudden onrushing of water. Sometimes this causes loss of human lives. Colour of the river changes with little rainfall in the catchment. Steep hillside slopes, covered by natural forest, is an important feature. Rubber and pepper plantations are also noticed.

Stop 4: Ponmudi
The Ponmudi (Golden peak), with an elevation of 1074 m, is one of the highest points of the Western Ghats in this part of the State (Fig. 11). It is at a distance of 15 km from Kallar. The way to Ponmudi cuts across hills winding through 22 hairpin bends. As elevation increases with every bend, the road is popularly known as the 'Ghat Road'.
Steep hill side slopes and deep valleys are common. Small stream and slope wash are observed. The road is through tropical rainforest, forest plantation, and tea plantation. The highest point has been developed as a tourist destination.

The ridge line around the highest altitude more or less follows a fold axis of a tight syn-form. Garnet-biotite gneiss and charnockite are seen in patches in and around Poonmudi. The charnockite found in Poonmudi area is known as Poonmudi type (Swamy, et. al., 1992). The gneisses have both well-developed mineral foliation and a composition banding trend along the direction N70W, coinciding with the regional foliation (Ravindrakumar, 1985). Both anti-form and syn-form fold axes were traced in this area with topographic expression of valley and ridge, respectively. This hill complex is oriented in NW-SE direction, and is a structural block between two sets of major lineaments in Kerala. It is the source of two major rivers of Kerala- the Vamanapuram and the Karamana. The hill crest is seen in two patches, which can be considered as the residual surfaces in this part of the Western Ghats, altitudinally comparable to the mid-Tertiary surface identified by Gunnell (2001). A tight synclinal axis in charnockitized garnet-biotite gneiss is identified in one of the hill crests near Poonmudi hill resort (Hansen, et. al., 1987). This syncline is represented by a ridgeline in NW-SE direction, with a dip slope of 70-80. The abrupt rise of the hill and convex slope indicate structural control and dominance of slope wash. It substantiates the theory that Western Ghat scarp is structurally controlled and has developed due to faulting in different geological time scales. The boundary between the Khondalite (garnet-sillimanite metapelites) and the Charnockite massif in south Kerala is traceable along the deep valley of Kallada-Achankovil shear zone, lying to the north of the Poonmudi hill complex. Remnants of planation surfaces at various altitudinal levels and comparable knick points marked in river profile indicate that this area was subjected to polycyclic development (Chattopadhyay and Mahamaya, 2004).

Erosional surfaces or planation surfaces developed during different geological era had experienced subsequent structural disturbances that had triggered renewed
erosional process, resulting in fragmentation of the surface and wearing down. Some patches are left as remnants. One such feature is noted to the north of the Ponmudi peak, which has developed as a marshland. The residual hills indicate the level of pre-existing surfaces, developed in this area. The valleys along the hill slope are covered by temperate shola forest, whereas the ridges are under grass cover. The subdued foothills (pediplain) are clearly visible from Ponmudi.

Day 3: 02/11/2017
Transect-II: Trivandrum to Varkala, Kollam, Ashtamudi, Chavara, Alappuzha and Kumarakom
Stay at Kumarakom.
The day's trip starts from Trivandrum and moves towards north following National Highway 34. This trip will traverse lateritic terrain, sand ridges, mudflats, Kuttanad deltaic plain and backwaters. Geologically it will move from a Crystalline terrain to the Recent sediments and landforms of Anthropocene.

Stop 1: Sedimentary Cliff at Varkala
The first stop at Varkala is about 40 km to the north of Thiruvananthapuram. It is one of the Geosites described in detail in the handbook on Geosites (proposed to be distributed during the Conference). It is a laterite cliff developed on sedimentary part of the Warkali (Mio-Pliocene) deposits (Fig. 12 and 13). The cliff section is marked in patches. Geologically it is a single uplifted block dissected by running water. The Varkala cliff is also affected by subterranean flow of water, resulting in removal of underlying clay materials and accelerated retreat of the cliff face. The Papanasam beach in front of the cliff at Varkala is a socio-religious place. The Hindu community uses Papanasam beach to perform religious rites for the departed souls.
Stop 2: Kollam-Asthamudi Lake
The Thiruvananthapuram to Kollam coast is rugged with exposure of crystallines, but it also has sedimentary rocks. To the north of Kollam, particularly at the Asthamudi River mouth, the coast is composed of permeable recent sediments. The width of the coastal plain increases here. The on-land Cenozoic deposits attain the maximum thickness. The maximum width is around Ambalapuzha, around 100 km to the north of Kollam. The Asthamudi Lake (64 km²) at the mouth of Kalada River is a coast-perpendicular backwater. It provides the facilities of a natural harbour. Kollam was a well-known natural port in historical past. Hard rocks bordering the mouth of the Asthamudi outlet is traceable offshore. Evidences of recent subsidence are traceable all around the lake. It is the second Ramsar Site (Wetland of International importance) in Kerala. The Neendakara fishing harbour, the largest fishing harbour in Kerala, has been developed in the mouth of this lake.

Stop 3: Chavara Placer Deposits
Permeable coast with recent sediment deposits are found after crossing Neendakara fishing harbour. The road traverses through sandy coastal plain. Kerala coast is well known for beach placers or heavy mineral deposits (locally known as black sand deposits). Chavara is famous in the country for high grade Ilmenite-rich beach and sand dune deposits. The important features notable in this stop is beach placer deposit, which is reworked through wave action. Palaeo-beach ridges in this locality are impregnated with black sand deposits at greater depths. Indian Rare Earth (IRE) and Kerala Mineral Mining Limited (KMML), the two industries set up for processing placer deposits by Government of India and Government of Kerala, respectively, have their factories located at Chavara coast. The coastline here is affected by erosion and needs regular nourishment.

Stop 4: Thottapally Bar Mouth
The road to to Thottapally passes through a sandy plain composed of palaeo-beach ridges. Thotapally bar mouth borders a mudflat and a palaeo-spit. Presence of mudflat along the coast, not associated with any major river, indicates existence of an outlet carrying riverine deposits. Studies indicated existence of a larger Vembanad basin having a major opening through this area (Chattopadhyay, 2002). Thotapally bar mouth, to the west of Thottapally spill way, is a remnant of an earlier opening to the sea or a palaeo-river mouth. The spill way was installed to check sea water ingresson and also to facilitate quick dispersal of flood water from the Kuttanad delta area. The project was not very successful as the general slope of the area supposed to be drained, is towards north. The notable features are extensive mudflat, palaeo-spit and the boundary between sandy plain and clay belt (Fig. 14). Half-decomposed and in-situ tree trunks found during excavation of clay in the nearby paddy fields indicated the existence of a good plant cover in the past, and also subsidence. The
clay belt, part of the Kuttanad delta, is the zone of subsidence. Thottapally mouth is characterized by bar formation, which is a common coastal process in Kerala. The bars are usually eroded during monsoon months and formed during calm period. A chain of sand dunes is found radiating from this point (Fig. 14).

**Stop 5: Alappuzha/ Block Reclamation Clay Belt**

Geologically this area is composed of recent sediments dominated by sand. Alappuzha town has grown on the flat sandy plain. The coast is mostly accreted. The coastal water here also experiences formation of 'Mud Bank' (suspended colloidal mud), which acts as wave breaker. As a result, the sea is calm and the coastline is protected. Mud banks also act as fish aggregation point. Formation of mud bank varies over the years. Proper explanation for this feature is still awaited.

Alappuzha town is referred to as Venice of the East due to the presence of canals and water bodies within and around the city. Waterways have been developed extensively and people use the water transport. It is a historical port town, developed in the 19th Century, and is famous for coir products. Houseboats and cruise in the backwaters are main tourist attractions.

The Kuttanad area lies to the east of this sandy belt and borders southern fringe of the Vembanad Lake. It presents a deltaic landscape formed by the the Pamba, the Achankovil and the Manimala river systems. Part of the Vembanad Lake in front of this delta has been reclaimed and compartmentalized in several blocks, popularly known as Block Reclamation, for agricultural purposes. Block reclaimed areas and parts of this deltaic landscape lie 1 to 2 m below the mean sea level. Therefore, for agricultural activities, dewatering is required during the post-monsoon period. The whole area is clay-rich, with an organic layer in the subsurface, indicating subsidence. Embankments all around the rivers and water courses protect this area from flooding. This inland delta owes its present formation to sea level change (Chattopadhyay, 2002).
Day 4: 03/11/2017
Transect-III: Kumarakom to Thanneermukkom, Muzaris, Angadipuram & Kozhikode
Stay at Kozhikode.
This transect begins from Kumarakom, a backwater tourist spot on the east bank of the Vembanad Lake in the outskirt of Kottayam town. Topographically flat, this area is part of the lacustrine plain/alluvial fan developed along the eastern border of the Vembanad Lake. The transect will cross the coastal plain-lowlands, composed of recent sediments. It will then move across the lateritic midlands to reach Angadipuram and then further north to Kozhikode.

Stop 1: Thanneermukkom Barrage - Vembanad Lake
The Vembanad Lake, with an area of 205 km² and spreading over Ernakulam, Alappuzha and Kottayam districts, is the largest lagoon in the west coast. It is fed by seven major rivers (Fig. 15). This water body is the classic example of a coast-parallel backwater. Bordering the Vembanad Lake there are three sets of beach ridges signifying transgression and regression. The lake has been declared as a Ramsar site. Thanneermukkom Barrage has been constructed across this lake to regulate salt water flow from the Kochi mouth to the southern end to facilitate rice cultivation. This barrage has divided the lake into two halves: southern part has turned into a fresh water body, whereas the northern part continues to receive tidal flow and maintain its brackish character. The lake ecosystem has changed and it has impacted fish breeding and other aquatic lives. There are debates on viability of this barrage and strong opinion to throw the barrage open to regain its brackish water character.

Fig. 15.
IRS-1B image FCC of the central part of Kerala, showing sand ridges to the west of Vembanad Lake, block reclamation areas, the wide deltaic plain, Thanneermukkom barrage and the backwaters.
Stop 2: Muziris
The route to Muziris passes through Ernakulam city, the main port city and industrial hub of Kerala. It moves through a sandy belt (glass sand deposits) and crossing the Vembanad Lake it passes through a low-level laterite terrain. Most of the laterite hills have been removed and the road appear to be on a flat terrain. Muziris was an ancient seaport and an emporium for international trade developed at least by the 1st Century CE. This place was mentioned in the bardic Sangam literature and in a number of classical European history. There are attempts to find exact location of Muzaris. With available archeological and historical evidences its location is approximately co-terminus with Kodangalur. It is suggested that the coastline has shifted during the last two millenniums and once a seaport, it is now found to be located well inland. Muzaris lost its glory with the shifting of the coastline. Finally, a devastating flood in 1341 opened the present Kochi mouth and the course of the Periyar River changed. Now Government of Kerala took special effort to develop this area as the largest heritage conservation project in India.

Stop 3: Angadipuram
The road from Muziris to Angadipram passes through wide lowlands associated with the Periyar River system, the Kole lands (low-lying alluvial basins) and the lateritic midlands of central Kerala. Francis Hamilton Buchanan, a medical officer in the services of East India Company, first reported laterite from Angadipuram area of Malapuram district in Malabar region of Kerala during his travels in 1800-01. Mr. Buchanan described it as an 'Indurated Clay' and gave it the name 'laterite' after the Latin word 'lateritis', meaning bricks. He found many constructions where laterite bricks were used. Geological Survey of India recognized Angadipuram as the National Geological Monument for Laterite in India and established a plaque there during the International Conference on Lateritisation, held at Thiruvananthapuram in the year 1979 (Fig. 16). General elevation of this area is 60 m. Laterite landforms consist of mesa, hills,
mounds, ridges and slopes. As a cap it develops on all types of rocks. The chemical characteristics of laterites depend on the chemical composition of the underlying rocks. Iron content in laterite profile is found to decrease with depth (Fig. 17). At Angadipuram the laterite has developed over the rock types of pyroxene granulite, charnockite and migmatic. Chemical composition of laterite here is given in Table 3.

![Decrease in iron content with depth and increase in silica and aluminum (clay) content was seen in the profile.]

Fig. 17.
A typical laterite profile and schematic to show relative abundance of Fe, Si and Al at different depths (source: A. K. Kasturba, 2014. Laterite monuments of Malabar Region, Western India).

| Table 3: Chemical composition of laterite in Angadipuram |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Element        | SiO\(_2\)       | Al\(_2\)O\(_3\) | Fe\(_2\)O\(_3\) | TiO\(_2\)      | NaO\(_2\)      | KO             | CaO           | MgO           |
| Per cent       | 32.0            | 29.38           | 17.38           | 2.05           | 0.95           | 0.27           | 0.3           | 0.2           |

Day 5: 04/11/2017
Transect-IV: Kozhikode to Kannur, Taliparamba, Bekal Fort, Kasargod & Mangalore
Stay at Mangalore.
This last transect of the field trip starts from Kozhikode and proceeds towards the north along coastal plain and then traverses various lowland features and lateritic landscape in the Malabar region. Kozhikode, one of the three important cities in Kerala, has a long history. As a spice trade centre this city enjoyed international trade connections even before CE. The trade continues now for several centuries, and in olden days there were competitions among the European nations to capture the hinterlands of Kozhikode, known for spice and timber production. Vasco Da Gama landed in Kozhikode coast in 1498. During the Colonial period Kozhikode was one of the most important towns in the Malabar region.

Topographically, this area is characterized by 'Half Orange Relief, a feature developed in tropical rainforest area, where there is excessive production of sediments during monsoon and sudden drop of slope. The slopes at the local level are graded, and denudation and deposition attain equilibrium.
Stop 1: Kannur - Laterite Landscape

The road from Kozhikode to Kannur passes through the densely populated and intensively used coastal plain. Laterite surfaces have developed extensively in this part and spread from the coastline to the foothills. Mesa landforms are well developed in parts of Kannur and Kasaragod districts. Formations of sour plates are also evident in places. All types of rocks have been lateritised (Fig. 18). A typical laterite section on crystalline rock consists of a humus zone/crust, pebbly zone, vermiform laterite, lithomarge, weathered rock, partly weathered rock and rock. In case of sedimentary rocks in Kannur, the laterite profile shows the sequence of crust, vermiform laterite, sandstone, alternating layers of ball clay and lignite, vermiform laterite and china clay (Fig. 19). Presence of vermiform laterite at two different levels perhaps indicates two different cycles of lateritisation. Laterite benches are seen exposed in Kannur coast (Fig. 20).

Fig. 18.
Map showing distribution of Laterite mesa on different rock types in Kannur (earlier Cannanore) district (source: Narayanaswamy and Chattoapdhyay, 1996).
Fig. 19.
Typical laterite profiles in Kannur district
(source: Narayanaswamy and Chattoapdhyay, 1996).

Fig. 20.
A wave-cut laterite bench along the Kannur coast.
Stop 2: Taliparamba - Kuppam

The route here follows the Kuppam River, which is structurally controlled and appears to be indented within the laterite surfaces. The road on both sides of the river has developed on mesa surfaces. Step like landforms from lower to higher elevation is well evident in this transect. Development of classic laterite landform is noted here (Fig. 21). An elongated residual hill devoid of laterite cover at an altitude of 254 m is surrounded by lateritic mesa surface at 120-160 m. The scarp face cutting across different altitudinal range and surrounding the mesa surfaces, is developing through headward erosion of streams and parallel slope retreat. As a result, a single mesa surface is dissected into a number of surfaces along the weaker planes or line of denudation, manifested by valleys. A major break in slope is marked at 170 to 180 m and the minor breaks are at 140 m, 100 m, and at 90 m, bordering the valleys (Chattopadhyay, 2004).

![Geomorphological map of a laterite terrain in Chattiyol-Kunduvati area](source: Chattapadhyay, 2004).
Flat hard crust (duricrust) surfaces without any soil cover are notable features in the lateritic terrain (Fig. 22, 23). Formation of 'soup plate' is also an important aspect of laterite morphology in this area (Fig. 24). These are colluvial-alluvial basins of various dimensions over the laterite surfaces. There are various theories for the formation of soup plates. McFarlane (1976) reported this type of feature in Africa and discussed some possible causes of its formation. Twidale (1987) considered these features as sinkhole on laterites. Structural deformation and collapse at the weathering front within laterite profile have also been suggested as possible mechanism. These colluvial-alluvial basins are used for paddy cultivation in some areas. It is also found that due to slope recession and headward erosion some of the soup plates are drained out through nearby streams. Most of the hard crust areas are left as 'wastelands'. Due to high rainfall, grasses grow luxuriously after the monsoon.

Fig. 22. A typical duricrusted lateritic terrain, with few greener patches of skeletal soil.

Fig. 23. A closer view of a duricrust laterite surface.

Fig. 24. Close view of a ‘soup plate’ within the laterite surface.
Stop 3: Bekal Fort
Bekal Fort, around 300 years old, situated on the coast around 15 km south of Kasaragod is an example of laterite built structure (Fig. 25). This is the largest fort in Kerala. It mostly served as an important military station during different historical periods, especially during the reign of Tipu Sultan, but it never was a seat of power.

Fig. 25.
Bekkal Fort, a tourist destination.

Stop 4: Kasaragod
Extensive laterite mesa surfaces are found here. It is the continuation of the laterite surfaces noted in Kannur area. The slopes of these vast flat areas are clay-rich and accommodate luxurious vegetation. Depth of the laterites profile here is more than 15 m at some places. A special feature called ‘Surangam’ is found here. This is a man-made structure, dug within the laterite hillocks to collect water. Valleys formed within the hard crust laterite surfaces are like gorges with greater width at the bottom as compared to the width at the surface. Laterite landscape is also reported to have piping in some areas. Management of hard crust laterite is a challenge. The tour ends at Mangalore for night halt.

Day 6: 05/11/2017
Mangalore to New Delhi by Flight
Stay at New Delhi.
References


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Ministry of Earth Sciences
Government of India

For Young Geomorphologists

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Geomorphological Field Guide Book

on

KONKAN & GOA COASTS

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Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
## Geomorphological Field Guide Book on Konkan and Goa Coasts

### Itinerary

<table>
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<tr>
<th>Day</th>
<th>Places from - to</th>
<th>Stay</th>
</tr>
</thead>
</table>
| Day 1 | Arrival at Panaji (Goa)  
Field excursion from Panaji to Ratnagiri (Maharashtra) | Ratnagiri |
| Day 2 | Field excursion, North of Ratnagiri | Ratnagiri |
| Day 3 | Field Excursion, South of Ratnagiri | Ratnagiri |
| Day 4 | Field excursion from Ratnagiri to Malvan | Malvan |
| Day 5 | Field excursion from Malvan to Panaji.  
Depart from Panaji. |           |
A. THE KONKAN AND GOA COASTS: AN INTRODUCTION

A 500-km long coastline along the Arabian Sea, extending from the confluence of the Damanganga River with the sea in the north to the confluence of the Terekhol River with the sea in the south, and a narrow coastal plain adjoining this coast, is a distinct physiographic entity of the Maharashtra state of India. This coastal belt forms part of a rugged terrain consisting of hills, plateaus and plains, which are collectively known traditionally as the ‘Konkan’ (Fig. 2). People here mostly speak in a dialect called the ‘Konkani’. Eastward, the Konkan region is separated from the upland Maharashtra by a steep west-facing escarpment of the Sahyadri Mountains or the Western Ghats. The width of the Konkan coastal belt varies from 40 to 50 km. Administratively, it falls within the districts of Palghar, Thane, Raigad, Ratnagiri, Sindhudurg and Mumbai.

Fig. 2. Konkan region in Maharashtra. Map on the right shows relief from SRTM image.

GEOMORPHOLOGICAL BACKGROUND

Before describing the morphological characteristics of the coastal landforms at the field sites, it may be worthwhile to provide a brief account of the salient features of the Konkan region, of which the coastal sector forms a part, as well as the major environmental factors that influence the coastal development.

Physiographic Divisions of the Konkan Region

On the basis of lithology, geomorphic configuration, nature of hinterland and climate, Konkan has been divided into the North Konkan, Middle Konkan and South Konkan. This 3-fold division is also reflected in the broad physico-cultural zonations in the region (Dikshit, 1986).
**North Konkan:** This coastal belt lies roughly between Bordi-Dahanu in the north and Karanja in the south (Fig. 3). It is characterized by N-S oriented forested hill ranges and a small plateau (~350-m above sea level; ASL), formed of the Deccan Trap rocks with intertrappean beds. The major streams draining the area are the Surya, Tansa, Vaitarana, Prinjal, Ulhas, Kalu and Bhatasai, with narrow flood plains along them. Courses of some streams like the Vaitarana are distinctly controlled by lineaments at places. The Ulhas plain, covered by brown silt, is most probably a marine planation surface of early Quaternary period (Dikshit, 1986). North Konkan receives an annual rainfall of 1500 mm and more.

![Fig. 3. Map of the major coastal sites in Konkan.](image)

**Middle Konkan:** The coastal belt from Uran to Shrivardhan forms the Middle Konkan, where the forested hills are more prevalent in the central part, with heights of 300-500 m ASL, and are formed dominantly of Deccan basalt. Dikshit (1986) identified most of these hills as ‘residual hills’, and suggested a planation surface at about 550 m ASL. The major streams are the Amba, Kundalika, Kal and Savitri, which appear to be lineament-controlled in most parts.
South Konkan: This is the longest stretch of the Konkan, and has the distinctive feature of 8-12 m thick capping of laterite over much of the terrain. Barren lateritic plateaus (150-200 m ASL), deeply entrenched stream channels and the piedmont plains at the foot of the Sahyadri escarpment are the significant land facets, and bear the imprints of lithological control (Karlekar, 1981). The major streams are the Vashshthi, Shastri, Kajavi, Muchkundi, Arjuna, Vaghotan, Gad and Karli. The laterite cover gets progressively reduced to the south of Tarele. In contrast to the landforms of the North Konkan and the Middle Konkan, the landforms here are dominantly influenced by granite and gneiss formations, especially around Kankavali, Kudal, Sawantwadi, Malvan and Vengurla. The area is rich in minerals. Iron, manganese, bauxite and silica sand are the important mineral reserves.

Division of the Coastal Sector

The coastal sector, characterized by plains, shoreline terraces, sand dunes, cliffs, numerous sandy pocket beaches, tidal inlets, creeks and estuaries, shows a great amount of variability from north to south. The landward margin of the coastal hinterland can be identified as the north – south hill ranges in the central part of Konkan, roughly parallel to the shore. The coastal strip is wider in the north than in the south. On the basis of the impact of tidal incursion and the tidal range during the spring tide and the neap tide, Konkan coast can be divided into macro-, meso- and micro-tidal regions (Table 1).

Table 1. Division of Konkan coast as per selected parameters (as determined by author)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Macro-tidal coast</th>
<th>Meso-tidal coast</th>
<th>Micro-tidal coast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring tide range (m)</td>
<td>&gt;3.5</td>
<td>3.5 – 2.0</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>Neap tide range (m)</td>
<td>&gt;2.0</td>
<td>2.0 – 1.5</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Tidal incursion limit along rivers (km)</td>
<td>40</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Coastal sector</td>
<td>Dahanu to Revas</td>
<td>Revas to Ratnagiri</td>
<td>Ratnagiri to Redi</td>
</tr>
</tbody>
</table>

Climate and its Effects on the Coastal Processes

The climate of the Konkan coastal belt shows a regular seasonal variation dependent upon the alternating southwest and northeast monsoon during a year. December to March is relatively cool with northeast winds. The weather is dry and the cloud cover is very little. April and May are hot, when the winds are light and variable with sea breezes on the coast. June to September is the season of southwest monsoon. Winds on the sea, in this period, are south-westerly and westerly. The winds on the coast, however, are mainly westerly. This is the season of high rainfall. October and November are marked by light winds. Occasional tropical cyclones originate in the Arabian Sea during this period. The period from the end of the southwest monsoon to its recommencement is usually identified as a fair-weather season.

Table 2 provides the average weather characteristics along the three coastal divisions. Based on these characteristics February to May can be treated as Pre-monsoon season along
the coast, June to September as monsoon and October to January as Post-monsoon season. Rough to very rough seas occur during the monsoon season. Moderate to heavy swell waves also persist along the coast during this season.

The width of the surf zone and the breaker zone decreases considerably during fair weather season, when the height of the breakers and the number of waves in a breaker decrease significantly. There is hardly any change in wave period from monsoon to fair weather season. During monsoon the northern ends of the beaches experience high wave energy. A clear shift of energy condition takes place from the monsoon to the post-monsoon season. During monsoon period, the waves are steep everywhere, and the breakers have short wave periods. The sediment supply through the streams is high. These two factors together increase the quantum of sediments in the waves.

Table 2. Weather and waves along the Konkan coast

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Month</th>
<th>North Konkan</th>
<th>Middle Konkan</th>
<th>South Konkan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (mb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>1010</td>
<td>1010</td>
<td>1011</td>
</tr>
<tr>
<td>July</td>
<td>1004</td>
<td>1006</td>
<td>1007</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>1011</td>
<td>1010</td>
<td>1011</td>
<td></td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>73</td>
<td>73</td>
<td>72</td>
</tr>
<tr>
<td>July</td>
<td>85</td>
<td>89</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>80</td>
<td>82</td>
<td>82</td>
<td></td>
</tr>
<tr>
<td>Dominant wave direction (&amp; % days)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>NW (56)</td>
<td>W (64)</td>
<td>W (53)</td>
</tr>
<tr>
<td>July</td>
<td>W (55)</td>
<td>SW (48)</td>
<td>W (57)</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>NW (56)</td>
<td>E (48)</td>
<td>W (41)</td>
<td></td>
</tr>
<tr>
<td>Wind speed (knot)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td></td>
<td>3 - 8</td>
<td>3 - 7</td>
<td>5 - 11</td>
</tr>
<tr>
<td>July</td>
<td>6 - 8</td>
<td>11 - 13</td>
<td>10 – 14</td>
<td></td>
</tr>
<tr>
<td>October</td>
<td>4 - 6</td>
<td>3 - 5</td>
<td>5 - 8</td>
<td></td>
</tr>
</tbody>
</table>


Waves, Tides and Near-shore Processes

Variation in sea waves and tidal waves, their intensity and frequency, their approach, height and persistence, are the main factors that influence the processes along the Konkan coast. There is a remarkable north-south and seasonal variation in these attributes all along the coast. The variations are site specific within the major regions.

Wind direction and wind speed also show definite trends from north to south (Table 2). It is found that the waves are westerly in pre monsoon period on middle and south Konkan coast and north westerly on northern coast with a speed varying between 3 and 8 knots. The south Konkan experiences winds of 5 to 11 knots in this period. Monsoon is a period of westerly to southwesterly waves with a speed exceeding 10 knots along major part of Konkan coast. The wave approaches and the wind speeds given in Table 2 can change locally due to considerable refraction as the waves approach the indented shoreline. Waves become steeper near the shore especially during monsoon.
On the basis of wave heights two distinct seasons can be identified, namely, monsoon (June to September) and fair-weather (October to May). Wave heights do not normally exceed 2 m in fair weather (Table 3). During monsoon, the waves often exceed 5 m in height, especially along the South Konkan coast. Long-period waves, with a wave period of 10 to 12 seconds, dominate the fair-weather season. During monsoon, the wave period decreases to 3 to 6 seconds. Towards the end of monsoon the wave period increases to 10 seconds, indicating the arrival of swells.

Table 3. Waves and currents (as measured by the author)

<table>
<thead>
<tr>
<th>Wave character</th>
<th>Time period</th>
<th>Revas</th>
<th>Ratnagiri</th>
<th>Redi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave height (m)</td>
<td>Fair weather</td>
<td>1.0 – 2.0</td>
<td>1.0 – 2.0</td>
<td>1.0 – 1.5</td>
</tr>
<tr>
<td></td>
<td>Monsoon</td>
<td>3.0 – 3.5</td>
<td>4.0 – 4.7</td>
<td>4.0 – 5.0</td>
</tr>
<tr>
<td>Wave period (s)</td>
<td>Fair weather</td>
<td>10.0 – 12.0</td>
<td>10.0 – 12.0</td>
<td>&lt;10.0</td>
</tr>
<tr>
<td></td>
<td>Monsoon</td>
<td>4.0 – 6.0</td>
<td>4.0 – 6.0</td>
<td>3.0 – 6.0</td>
</tr>
<tr>
<td>Tidal current velocity (cm/s)</td>
<td>Fair weather</td>
<td>70 - 90</td>
<td>10 - 20</td>
<td>&lt;10</td>
</tr>
<tr>
<td></td>
<td>Monsoon</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Near-shore Zone**

The specific near-shore environment on the Konkan coast is influenced strongly by the factors mentioned above. The breaker zone near the shore is about 200 m wide from June to September, and the very high breakers are produced during this period. Wave breakers during the monsoon are of spilling and plunging type. During fair-weather period, the breakers are characterized by low, surging or collapsing waves. The surf zone width exceeds 200 m during the monsoon and gets reduced to less than 25 m during the fair weather.

Measurement of the long shore currents at a few places reveals that these currents are significant especially to the south of 18° N. The currents are southeastward during monsoon and move with an average speed of 30 to 40 cm/s. During fair weather these are north- northwestward, and usually attain a speed of 8 to 20 cm/s. The direction and the speed of the longshore currents change locally, influenced mainly by the local coastal configuration. North to NNW currents are the strongest in October and the SE currents are powerful in July. During monsoon the nearshore areas are also dominated by rip currents.

**Tides**

Konkan coast experiences mixed semi-diurnal tides with a tidal range of less than 2 m to more than 3.5 m. The tidal range gradually increases from south to north, i.e., from 1.5 m at Redi to 5.4 m at Valsad. Tidal currents are very weak along the South Konkan coast. Here the velocity rarely exceeds 10 cm/s. Strong tidal currents with a velocity of 70-90 cm/s have been recorded along the North Konkan coast. Table 4 shows the average spring and neap tide and the tidal range at important field sites along the Konkan coast.
Table 4. Tidal range at field sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (deg., min.) N</th>
<th>Longitude (deg., min.) E</th>
<th>Spring tide height (m)</th>
<th>Neap tide height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaygad</td>
<td>17, 18</td>
<td>73, 14</td>
<td>2.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Ratnagiri</td>
<td>16, 59</td>
<td>73, 18</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Musakagi</td>
<td>16, 37</td>
<td>73, 20</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Vijaydurg</td>
<td>16, 33</td>
<td>73, 20</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Devgad</td>
<td>16, 23</td>
<td>73, 23</td>
<td>1.9</td>
<td>1.3</td>
</tr>
<tr>
<td>Malvan</td>
<td>16, 03</td>
<td>73, 28</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Vengurla</td>
<td>15, 51</td>
<td>73, 37</td>
<td>1.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>


### Sea Levels and Sea Level Fluctuation along the Coast

There is no monitoring station along the Konkan coast to measure the actual sea level fluctuation, and so a definitive chronology of sea level events in modern times is still awaited (Karlekar, 2000). Many of the geomorphological features on the coast, however, indicate a slightly higher sea level during the early Holocene period. Cliffs formed by wave action and shore platforms are very frequent along the coast. The shoreline terraces (Fig. 4) and the two / three generations of fossil dune ridges (Fig. 5) provide some convincing evidence of former shorelines. The wide coastal plains and the narrow shoreline terraces appear to be covered with Tertiary sand.

![Fig. 4. An example of shoreline terraces along the Konkan coast.](image1)

![Fig. 5. A typical fossil beach dune ridge along the Konkan coast.](image2)

The land between 2 and 10 m ASL provides evidence for numerous shore marks (Karlekar, 2000). Extensive flat plains on the late Holocene sediments suggest their development from tidal basins. There is no data to suggest that major storm accretion happened along this coast for at least the last 3000 years, and the fossil deposits found inland cannot be attributed to stormy episodes.

About 6000 BP the sea was more or less at the present level. Between 6000 and 2000 BP the sea level gradually rose to 6 m ASL. Studies so far suggest that the highest sea level
was attained around 3000 years BP (Guzder et al., 1975; Dikshit, 1976; Karlekar, 1981; Kale and Rajaguru, 1985; Bruckner, 1987; Hashimi, 1995). There is no convincing data yet to mark the sea level changes during the last 500 years.

Despite the lack of actual sea level measurements, some geomorphic features along the coast have been used to infer a general rise in sea level during the last few years. The features are: breaching of the beach ridges, scouring of ancient tidal channels, submergence and decaying of mangroves (Karlekar, 1986), breaching and undercutting of anti-erosion walls, appearance of offshore mud on sandy beaches and an overall increase in the salinity of well water along the coast. The disaggregation of sand accumulation forms and the redistribution of sediments in the bays and the creeks, e.g. at Shrivardhan (Karlekar, 1997), Kelshi (Karlekar, 2000) and Karli, also indicate a recent rise in sea level along the Konkan coast.

**Landforms along the Konkan Coast**

The shoreline all along the Konkan coast is broken by numerous headlands and promontories, which are the sites of steep sea cliffs, beautiful sandy pocket beaches, drowned river valleys, small tidal inlets and major river creeks. One is thrilled by an almost regular sequence of headlands and tidal inlets. Narrow, flat and low shoreline terraces, covered with a thin apron of coastal alluvium, border the tidal inlets. These land facets have contributed immensely to the distinctiveness of the Konkan coast.

**Beaches of Konkan**

Konkan coast is dotted with innumerable, small, sandy pocket beaches (Fig. 6). Tables 5 and 6 provide a summary of the morphological properties of the beaches to be visited. Sandy beaches are predominant, but a few mud beaches do also occur, e.g., at Rewas, as also the shingle beaches, e.g., at Shekhadi. The sediment characteristics and the morphodynamics of these beaches are controlled mainly by the specific wave and tide environment related to seasons and tidal ranges. The entire beach zone consists of depositional facies formed by waves, wave-induced currents and associated flows. Wide beaches with a well-developed berm and beach face are characteristic of the fair weather period (Karlekar, 2014). These get transformed into narrow beaches with steep to very steep beach faces during the monsoon period, the degree of steepness and beach cutting varying from place to place.

![Fig. 6. A sandy beach along the Konkan coast.](image-url)
Most beach sediments are well sorted. Major differences in the grain size reflect the differences in wave energy levels. Tides are the main force in macro- and meso-tidal environments in north Konkan. Decrease in the velocity of tidal currents at ebb results in sediment deposition in the swash zone. The flood tide currents, on the contrary, induce erosion and cutting of the beach profiles. In addition to these daily changes, Konkan beaches also undergo periodic changes with the seasons. Low, flat, swell waves during fair weather period build up the berm or beach face, while the high, steep, storm waves during the monsoon cut the beach face (Karlekar, 1997). Flat beaches in Konkan are usually associated with the low and spilling breakers of fair weather, whereas plunging breakers front the steep beaches.

Table 5: Konkan beaches to be visited

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (deg., min) N</th>
<th>Longitude (deg., min) E</th>
<th>Length (km)</th>
<th>Beach type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Guhagar</td>
<td>17, 29</td>
<td>73, 11</td>
<td>6.0</td>
<td>Sandy, Pocket</td>
</tr>
<tr>
<td>2. Velneshwar</td>
<td>17, 22</td>
<td>73, 12</td>
<td>1.5</td>
<td>Sandy, Pocket</td>
</tr>
<tr>
<td>3. Varavade</td>
<td>17, 13</td>
<td>73, 15</td>
<td>4.0</td>
<td>Sandy, Pocket</td>
</tr>
<tr>
<td>4. Kalbadevi</td>
<td>17, 04</td>
<td>73, 16</td>
<td>5.0</td>
<td>Spit, Bar</td>
</tr>
<tr>
<td>5. Mirya</td>
<td>17, 01</td>
<td>73, 17</td>
<td>4.5</td>
<td>Bay head</td>
</tr>
<tr>
<td>6. Talashil</td>
<td>16, 01</td>
<td>73, 27</td>
<td>13.0</td>
<td>Sand bar</td>
</tr>
<tr>
<td>7. Devbag</td>
<td>15, 58</td>
<td>72, 57</td>
<td>06</td>
<td>Sand bar</td>
</tr>
<tr>
<td>8. Vengurla</td>
<td>15, 51</td>
<td>73, 37</td>
<td>03</td>
<td>Sandy</td>
</tr>
</tbody>
</table>

Source: Author.

Table 6. Beach properties as measured by the author

<table>
<thead>
<tr>
<th>Site</th>
<th>TR (S)*</th>
<th>TR (N)</th>
<th>Length (km)</th>
<th>Br. distance (m)</th>
<th>Br. W surf zone</th>
<th>Swash</th>
<th>Beach W (m)</th>
<th>Slope (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guhagar</td>
<td>2.6</td>
<td>1.5</td>
<td>6.0</td>
<td>77.8</td>
<td>33.4</td>
<td>22.2</td>
<td>18.2</td>
<td>6.3</td>
</tr>
<tr>
<td>Jaygad</td>
<td>2.7</td>
<td>1.6</td>
<td>2.4</td>
<td>105.6</td>
<td>27.1</td>
<td>32.0</td>
<td>35.2</td>
<td>10.2</td>
</tr>
<tr>
<td>Ratnagiri</td>
<td>2.7</td>
<td>1.5</td>
<td>0.8</td>
<td>85.6</td>
<td>45.2</td>
<td>35.7</td>
<td>28.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Vijaydurg</td>
<td>1.8</td>
<td>1.4</td>
<td>0.6</td>
<td>98.1</td>
<td>32.7</td>
<td>43.3</td>
<td>41.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Devgad</td>
<td>1.8</td>
<td>1.3</td>
<td>0.5</td>
<td>87.8</td>
<td>26.5</td>
<td>50.4</td>
<td>50.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Malvan</td>
<td>1.9</td>
<td>1.3</td>
<td>1.7</td>
<td>159.8</td>
<td>35.1</td>
<td>23.5</td>
<td>64.5</td>
<td>4.9</td>
</tr>
<tr>
<td>Dabholi</td>
<td>1.5</td>
<td>1.3</td>
<td>2.3</td>
<td>151.7</td>
<td>34.3</td>
<td>15.5</td>
<td>48.6</td>
<td>12.1</td>
</tr>
<tr>
<td>Vengurla</td>
<td>1.5</td>
<td>1.2</td>
<td>5.0</td>
<td>102.6</td>
<td>22.4</td>
<td>24.7</td>
<td>66.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

*TR(S): Tidal range, Spring; TR (N): Tidal range; Neap, Br, Breaker.

Swash-aligned beaches (Davies, 1977) along this coast are found in the indented and irregular stretches. In some cases these are transformed to drift-aligned beaches during the monsoon. The ridge and the runnel and the rhythmic forms, such as the cusps, ripple marks, mega-ripples, crescentric bars, berms and the dunes, are the essential morphological
features seen on the Konkan beaches. A large variation in size, shape and location of these features is remarkable.

The quantum of swash and backwash is more or less equal on the fine sandy beaches, especially due to restricted percolation. On the coarse sandy and gravel beaches, however, the deeper percolation of swash waves causes the formation of steep beaches. Such beaches are too infrequent along the Konkan coast, and can be seen at places like Shekhadi, Uran and Karanja.

The sandy beaches are steep only during the monsoon when the maximum slope attained by a beach is as high as 7 to 11 degrees. The average beach slope during fair weather is 2 to 3 degrees or less. During monsoon the sands become poorly sorted and show a positively skewed, leptokurtic distribution.

Sediments on the Konkan beaches are subjected to reworking by aeolian, biological and coastal processes every year. Many beaches such as Kihim, Revas, Adhe, Anjarle, show a vertical sequence of fine sand, coarse sand, silt clay and mud even up to a depth of 40 cm. The subsurface sands are poorly to moderately sorted. The mud at depth is scoured, reworked and spreads on the beaches in monsoon (Kale and Awasthi, 1993). This phenomenon is especially seen at Avas, Revdanda, Kelshi and Adhe. This seems to be a recent event (Karlekar and Devane, 1995) and is restricted to meso-tidal beaches.

Konkan is also endowed with long, beautiful sandbars and spits, which are essentially the sandy beaches attached to the mainland at one end. Dandy, Revas, Revdanda, Devbag and Ubhadanda are some of the striking examples of sandbars on Konkan coast. These are usually the drifts aligned, built parallel to the line of maximum drift. The beach construction ends abruptly where littoral currents meet the coastline. At such locations the beach turns landward, at the entrance of tidal inlets. Spits like the one at Rewas, produced by the combination of drift and tide, show features of tidal and drift dynamics. The swash-aligned beaches on Konkan coast are crescentric beaches. A few spits end in one or more hooks or recurves, producing distal convexity.

Beach pits, low tide fans and mud balls are other important sedimentary structures characteristic of the Konkan beaches. The occurrence of mud on beaches is a recent phenomenon and probably indicates a slight rise in sea level.

Coastal Dunes

Sand dunes are a well-marked and distinct feature of this coast. On the backside of many beaches primary dunes with characteristic wind ripples can be easily recognized, which are followed landward by parallel ridges of secondary dunes. The embryo dunes, foredunes and backdunes are more conspicuous at Diveagar, Kelshi, Tambuldeg, Mochemad and Velaghar (Fig. 7). There is large variability in their morphology, orientation and the degree of preservation (Deswandikar and Karlekar, 1996).

On the narrow sandy beaches with a width not more than 50 m, the dunes are low and quite inconspicuous. On the wide sandy beaches, on the other hand, extensive dune systems can
be found to occur. The dune systems at Diveagar, Kelshi, Mirya, Sagartirth, Ubbhadanda, Mochemad and Velaghar are typical examples. The outer foredunes and the farthest backdunes are often higher than the central dunes. The foredunes actually form a dune wall sloping steeply seawards and gently landwards. The backdunes are more or less symmetrical but scattered. The scattered dunes give an impression that they are the residuals of ancient, continuous, foredune ridges. The interdune flats between the foredunes and the backdunes are occupied by low, discontinuous, shapeless and scattered mounds of blown sand. The foredunes, and to some extent the central dunes, are normally covered by plants like the Ipomoea creepers, which form a thin mat on the dune surface. These plants have helped in trapping the sand blown in from the beaches, and thus in building the dunes.

The most landward backdune ridge is often a partly lithified, aeolian sand mass. Some of the important coastal settlements like Nandgaon, Diveagar, Guhagar and Mirya are virtually on top of such lithified fossil dunes, comprised of aeolianites that are locally called the ‘Karal’ rocks (Dikshit, 1976; Deswandikar and Karlekar, 1996; Karlekar and Gadkari, 1998). These are the places of ample and shallow groundwater that is utilized by the inhabitants for drinking as well as for growing coconut trees.

**Sea Cliffs, Caves and Shore Platforms**

Impressive sea cliffs, sea caves and shore platforms characterize the rocky coast of Konkan. These features are usually found along joints, cracks and other weaker sections of the rocky headlands (Fig. 8).

The destructive impact of waves along this coast is often far greater than is generally realized (Karlekar, 1981, 1993). The headlands and promontories of the coast are subjected to shocks of enormous intensity, especially during the monsoon. Cracks and crevices are quickly opened up and extended. High-pressure spray of waves is forcibly driven into every opening. At any given time and place the actual form of the sea cliff and cave depends on the nature and structure of rocks exposed and the relative rates of marine erosion and subaerial denudation.
Cliffing is the dominant process on this coast. In general the cliffs in the area have a wave-cut bench at the foot. The predominant cliff face angle is commonly about 60 degrees. Average height of the cliffs is about 9 m. Overhangs and notches slightly above the influence of present-day waves characterize the lower sections of the cliffs. At places like Korlai, Hareshwar, Kolthare, Velneshwar, Jaygad, Agargule, Vetye, Kunkeshwar, Sarjekot, and Kondura the cliffs and caves appear to have been left high and dry due to recent fall in the sea level.

The near-absence of quarrying material at the foot of cliffs, insignificant mass movement on the forested upper sections and the lateritic cover on the cliff tops, especially in Middle Konkan suggest insignificant subaerial erosion. The spray marks, caving and undercutting, however, confirm strong marine erosion of the lower sections of the cliffs.

The shore platforms at the foot of the cliffs are also a striking feature in Konkan. Their average width rarely exceeds 30 m. The platforms are intertidal and are shaped by abrasion and water layer weathering. A low tide cliff of about 1 m height, bordering the seaward margin, is a typical feature of the platforms on the Raigad and the Ratnagiri coasts. The surface of the platforms all along the coast is dotted with innumerable shallow pools and potholes of varying sizes. The shore platforms are mainly produced on basalt but large number of lateritic platforms also exists, e.g., at Ambolgad, Devgad, Kunkeshwar and Bhogave.

The features like ‘Geos’ and ‘Blowholes’ are not very common along the Konkan coast. Few examples could be noticed at Korlai, Velneshwar and Hedvi.

**Estuaries and Creeks**

The estuaries and creeks on this coast are distinct, especially due to their tidal and fresh water regime (Fig. 9). They also exhibit a complex pattern of sediment input. The tidal inlets to the south of 18° N are mainly wave-dominated. Northern estuaries have a strong tidal control. Most of the estuaries on Konkan coast are NW – SE oriented and suggest a structural control in the tidal sectors of the streams. In North Konkan, the creeks and estuaries are found to be the bar-built and coastal-plain estuaries. Lengthening of ebb condition is an important aspect and is reflected in the tidal delay period (residence time) of about 1 to 2.5 hours (Karlekar, 1996). Imbalance between the length of the estuary and the contemporary tidal range is seen in the ponding of tidal water in the middle portion of some estuaries, e.g., at Kelshi and Anjarle.

Fig. 9. A tidal creek along the Konkan coast.
The major sedimentary features of the Konkan creeks and estuaries are the marsh and swamp edges, high and low tide flats, sand lenses, sand banks and islands and scoured channels (Karlekar and Keskar, 2014). These are produced by site-specific hydrodynamic conditions like wave action, flow velocities, turbulence, mixing and scouring. The mid-estuarine sectors are the areas of silty-clayey bars. The depth of these tidal inlets varies normally from 1 m near the head to about 4 m near the tidal mouth. Tidal water penetrates to a distance of more than 30 m in many estuaries, like at Amba, Kundalika, Dabhol, Arjuna and Karli (Table 7). The estuaries of Middle Konkan and South Konkan occur as narrow, elongated inlets with relatively little human interference. Some of the tidal inlets are known to have placer deposits (Karlekar, 2001).

Table 7. Major creeks, creeklets and estuaries of Konkan

<table>
<thead>
<tr>
<th>Name</th>
<th>Latitude (deg., min) N</th>
<th>Longitude (deg., min) E</th>
<th>Tidal incursion limit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kalbadevi Creek</td>
<td>17, 02</td>
<td>73, 17</td>
<td>06</td>
</tr>
<tr>
<td>2. Bhatye Creek</td>
<td>16, 59</td>
<td>73, 19</td>
<td>20</td>
</tr>
<tr>
<td>3. Purnagad Creek</td>
<td>16, 48</td>
<td>73, 20</td>
<td>20</td>
</tr>
<tr>
<td>4. Rajapur Creek</td>
<td>16, 36</td>
<td>73, 20</td>
<td>25</td>
</tr>
<tr>
<td>5. Vaghrotan Creek</td>
<td>16, 34</td>
<td>73, 23</td>
<td>25</td>
</tr>
<tr>
<td>6. Arjuna Creek</td>
<td>16, 23</td>
<td>73, 26</td>
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Freshwater flow during monsoon is one of the fundamental controls on salinity in these estuaries (Karlekar, 1996). A pronounced salt wedge during dry season is a dominant feature. High freshwater flow during the monsoon dilutes much of the salinity to a distance of 1-2 km in the estuaries. However, some salinity still remains in the lower column of the tidal waters. During the post-monsoon period salt wedges are re-established rapidly.

There exist several pools of high salinity and suspended sediment concentration in most of the Konkan estuaries. A substantial part of the suspended sediments entering the estuaries is deposited within the estuaries only. A large part settles on the mud flats and other areas outside the main tidal channel. The deeper sections act as sediment traps. Sedimentation in these estuaries appears to be governed by factors like length of the tidal inlet, tidal range and the process of flocculation.

Mangrove Swamps

Mangroves are thickly vegetated intertidal estuarine wetlands, confined to silty bog formation. Along the Konkan coast these are restricted mainly to the sheltered shore zones regulated by tidal flooding (Fig. 10). The most widespread genera of mangroves on this
coast are Rhizophora (red mangroves) and Avicennia (black mangroves). All the shrubs and trees in mangrove swamps are characterized by adaptation to the loose, wet substratum, tidal submergence and periodically changing salinity level. Prop roots and aerial breathing roots are the most frequent adaptations. Everywhere the mangroves are the nurseries for fishes and crustaceans.

The mangroves are usually found near muddy creek banks with fine silt and clay, which are rich in organic matter. Their dense growth can be seen in the tidal sectors of Ulhas, Amba, Savitri, Mhasala, Kalbadebi, and Rajapur creeks, where shores are free from strong waves and tidal velocities are not very high. Here, the vertical tidal range is 2-3 m. Important varieties of mangroves on this coast are Rhizophora mucronata, Rhizophora apiculata, Brugiera symnorhiza, Avicennia officinalis and Lumnitzera racemosa (Deshmukh, 1989).

Widespread destruction of many of these varieties has degraded the age-old mangrove ecology. This in turn has affected the sediment entrapment capacity of the mangroves, and hence the nutrient enrichment capabilities. Consequently, the mangroves at many localities are no longer able to act as feeding and nursery grounds for the commercially important fish varieties. Also, the degradation of the mangroves is making the coast more vulnerable to tides and waves. Since fish production is very important for the livelihood of the inhabitants and since coastline protection is also necessary, the mangroves along the Konkan coast need to be conserved on priority basis.

The Coast of Goa

The coastal tract in the state of Goa lies between 14°48' N and 15°48'N and between 75°40'E and 74°20'E. Lying adjacent to the Konkan coast of Maharashtra, this coastal belt is considered a part of the Konkan coastal belt. It is a narrow coastal strip located at the foot of the Western Ghats. The height of the Western Ghats here is nearly 1000 m, while the plians at the foothills lie at about 100 m ASL. The land between the foothills and the sea is about 40 km wide. This region is characterised by several small hills scattered all over the
area. Physiographically the region can be broadly classified into: (1) the coastal tract, (2) sub-Ghat region, and (3) the high ranges of the Western Ghats.

Temperature in Goa is moderate, with not much seasonal variation. May is the hottest month, while January and February are usually the coldest. Rest of the year usually experiences a tropical weather. Rainfall is copious, and is received mainly during the rainy season from June to September, when the whole of Konkan coastal tract receives high rainfall from the Southwest monsoon. The highest rainfall is received during July while the driest month is February.

Mining is one of the principal sources of Goa’s industrial and trade development. It offers considerable scope for employment also. Iron ore is the leading commodity for mining, and occupies the pride of place in Goa’s economy. Other mine resources include manganese ore and ferro-manganese ore. Some of the most productive and important mines are located in the northern and eastern parts of Goa.

Goa is also famous worldwide for its golden beaches. Several pocket beach segments are now open to international tourists, and these remain crowded almost throughout the year. The income generated by the state from these beach-based ‘tourism industry’ competes for high ranks with the revenue generated from mining and industries.

Agriculture is also an important economic activity in Goa. Fishing, both in freshwater and in open sea, is the most dominant economic activity along the coastal strip. Rice cultivation predominates inland. Goa has done much to develop its agriculture, and the farmers now get a better return for their labour. Rice along with fish is the staple diet of the people.

SOCIO-ECONOMIC ASPECT

The North Konkan coastal belt, to the north of Mumbai, has an average width of 15-20 km. The Mumbai-Delhi railway track and the Mumbai-Ahmedabad National Highway run through this coastal strip, and provide excellent glimpses of intensive garden farming, besides the views of rice fields. The region enjoys the advantages of a very effective transport network and a close link with Mumbai. The influence of Mumbai is significant in its primary economic activities and the occupational structure of the population. One frequently comes across large orchards of chikoo and mango, as well as coconut groves and dairy farms, all of which have a thriving market in Mumbai. Many large settlements in this plain work as contact towns and market centres of the Mumbai megalopolis. Nearer the lush green forested hills, inhabited by the tribals, the urban centres provide lucrative jobs to the tribal folks. Timber trade is an important activity near the hills.

The irregular coastal tract of Middle Konkan, often interspersed with hilly terrain, has its cultivated lands confined only to the narrow riverine plains and along the coastal flats. Croplands constitute less than 30% of the total area, where rice is the principal crop. Irrigation is highly localized. A relatively sparse population, with a density of 175 per sq km, lives in small villages and sometimes in widely spaced individual huts.
In the coastal tract of South Konkan, subsistence farming is dominant, as the area is largely stony and barren with shallow soils, interspersed with laterite plateau. Large-scale migration of people, especially men, from the region to Mumbai and its suburbs for job has disturbed the sex ratio. Many villages in this coastal belt are dominated by women who tend to the fields.
B. DESCRIPTION OF THE FIELD SITES

Day 1
Arrival at Panaji (Goa)
Travel from Panaji to Ratnagiri
Stay at Ratnagiri.

The field trip begins from Panaji (Goa). Goa coast is 135 km long, and is characterised by a rocky shoreline with innumerable pocket beaches. The northern coast of Goa looks more like the south Maharashtra coast, and is characterized by old and recent tidal flats, dune systems comprising of fore and back dunes, sea cliffs and shore platforms. The beaches to the north reveal a retrograding shoreline where erosion is dominant.

After landing at Goa International Airport we take the road to Ratnagiri by bus. The distance is about 175 km. En-route it is proposed to visit a few coastal tracts of central Goa coast, i.e., the Zuvari and Mandavi estuaries and the Miramar beach. A visit to the fort at Aguda is also proposed. Because of logistical purposes, the field excursion around Panaji and the North Goa beaches will be taken up on the last day of the tour.

The Mandavi and Zuvari estuaries form the largest tidal system along Goa coast (Fig. 11). The large embayment at the entrance of the Mandavi estuary, Aguada Bay has very complex flow patterns of tidal flow and sedimentation. The siltation in the channel is essentially due to deposition of the suspended sediments due to tidal flows, as well as sand incursion due to littoral drift. Mudflats are found mainly along such estuaries and creeks.

Miramar beach (Fig. 12) is 3 km long and 85 m wide. The dune zone at the back of this beach is short. The headlands at Aguda Fort, Dona Paula and Marmgao are 72 m, 35 m and 75 m high, respectively, and show sea cliffs having height of 10 to 12 m above sea level and narrow shore platforms with a width rarely exceeding 10 m.

Fig. 11. Mandavi and Zuvari estuaries of Goa
Fig. 12. Miramar beach near Panaji.
Day 2
Field excursion to the north of Ratnagiri
Stay at Ratnagiri.

On the second day the coastal sites north of Ratnagiri will be visited up to Ganapatipule.

This will help us in exploring the unique nature of the central part of South Konkan coast (Fig. 13). The tract between Ratnagiri and Ganapatipule is covered by thick secondary laterites (Fig. 14). Barren lateritic plateaux, deeply entrenched river channels, wide creeks and estuaries, beaches, cliffs and shore platforms are the significant land facets of the coast. The coastal plateau is 50-100 m high and the cover of laterite is 8-12 m thick.

**Fig. 13. Field sites from Keri to Ganapatipule.**

**Fig. 14. Road from Ratnagiri to Ganapatipule**

**Ratnagiri**: Sea cliffs, Shore platforms and Sea caves are the major landforms seen from Bhagavati Fort (or Ratnadurga) headland (Fig. 15). The headland is a 75 m tall promontory on the Ratnagiri sea shore. It has divided the Ratnagiri shore into northern and southern coastal segments.

Ratnadurga, popularly known as Bhagavati Fort, with an area of 120 acres, is situated on this hill. The fort is surrounded by sea. The Legendary Hero from Maharashtra during the Mughal Period, Chatrapati Shri Shivaji Maharaj won the fort in 1670 from the king, Adilshah. The fort was used as a watch tower for keeping vigil on the pirates. A lighthouse is situated in the fort, which guides the ships/vessel's travelling in the Sea (Fig. 16).

A beautiful temple to Goddess Bhagavati is also situated here. Devotees from far-flung areas visit the temple, especially during the famous Navaratri festival in October. The fort is in ruins now. One can see the entire Ratnagiri city from this fort.
Impressive sea cliffs, shore platforms and notches and caves characterize the coast (Fig. 17). The destructive impact of waves along this coast is often far greater than is generally expected. Clifining is the dominant process. Average height of the cliffs is around 9 m. Overhangs and notches slightly above the influence of the present-day waves characterize the lower sections of the cliffs. The near-absence of quarrying material at the foot of the cliffs suggests insignificant sub-aerial erosion. The shore platforms at the foot of the cliffs are a striking feature in the area. Their average width rarely exceeds 30 m. The platforms are intertidal and are shaped by abrasion and water layer weathering.
Fig. 18. Mirkarwada harbour and the Mirya Bay.

The caves on this coast have developed on basalts and laterite. A 7 m high cave in the area is fronted by a long narrow and deep channel, which is produced along the weaker zone. An all-weather port can be seen at Mirkarwada harbour in the southern part of Mirya Bay to the north (Fig. 18). The total area of Mirya Bay is about 6 sq. km. Since the construction of a commercial harbour in 1981, the 3.5 km long beach is suffering from severe erosion near the northern end, and severe siltation to the south (Fig. 18).

The modern beaches and dunes of the area are backed by old, fossilized beaches and dunes. The fossil deposits are more or less parallel to the shore. The deposits are calcareous, sandy and shelly in nature (Fig. 19). Mirya village is situated on such a fossil dune and beach ridge. The fossil deposits suggest a higher sea-level in this part of the coast 2800 years BP.

The Tidal inlet at Sakhartar is distinct, especially due to its tidal and fresh water regime (Fig. 20). The major sedimentary environments of the inlet are the tidal flats associated with the high tide, low tide, sub-tidal and inter-tidal regimes, as well as the sand banks, mangrove swamps and scoured tidal channels. The mid-inlet sectors are invariably the areas of silty-clayey bars. On an average the depth of the tidal inlet varies from 1 m near the head to about 4 m near the tidal mouth. Saline inter-tidal mud flats are the prime areas of sedimentation in the creek.

Fig. 19. A typical fossil dune and beach ridge profile near Mirya

Fig. 20. Google Earth image of the tidal inlet at Sakhartar.
The coastal stretch from Sakhartar to Ganapatipule is characterized by many small pocket sandy beaches, sea cliffs and caves (Fig. 21). There is large variability in sandy beaches, which is a result of wave environment. The entire beach zone consists of depositional facies formed by waves, wave-induced currents and associated flows.

Swash-aligned beaches on this coast are found along the indented and irregular stretches. In some cases these are transformed to drift-aligned beaches during the monsoon. The ridge, the runnel and the rhythmic forms such as cusps, ripple marks, mega ripples, crescentic bars, berms and dunes are the essential morphological features seen on these beaches.

Coastal dune is a well-marked and distinct feature of this coast (Fig. 22). On the backside of many beaches primary dunes with characteristic wind ripples and parallel ridges of secondary dunes can be easily recognized. The embryo dunes, foresdunes and backdunes are relatively more conspicuous at few sites. There is large variability as regards their morphology, orientation and the degree of preservation.

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**Day 3**

*Field excursion, South of Ratnagiri*

*Stay at Ratnagiri.*

The third day of the field visit will include coastal sites to the south of Ratnagiri and up to Ambolgad.

Near Ratnagiri one encounters a lignite bed below a lateritic cover. Called the Ratnagiri Lignites, this deposit is reported from Golap Kolambe plateau, just south of Ratnagiri. These are the beds of Carbonaceous Clay at sub-surface, underlying the lateritic cap. One of the important aspects of secondary laterites in the area is the occurrence of such carbonaceous clay below the lithomarge (Fig. 23). The lignite deposits exhibit a distinct unconformity with the underlying gravel bed, and yield abundant fossils woods, pneumatophores and fruits. The clay is older than 45000 years BP as indicated by palaeobotanical evidence. The occurrence suggests a higher sea level in the geological past, approximately by 37 m. The earlier environment was meso-tidal, as suggested by the species occurrence.
The coastal stretch is bestowed with numerous pocket sandy beaches and sand spits, especially at Bhatye, Ganeshgule, Gaonkhadi, Vetye and Ambolgad, tidal mouths at Bhatye, Pawas, Purnagad and Jaitapur, and sea cliffs at Bhatye, Ganeshgule and Ambolgad (Fig. 24).

In addition to these features, Bhatye and Gaonkhadi beaches and tidal mouths of some small streams in the vicinity are known for the occurrence of heavy mineral placer deposits, especially ilmenite (Titanium iron ore, FeTiO$_2$), containing 36.8% iron and 31.6% titanium (Fig. 25 and 26).
River channels, shoreline terraces, estuaries, mangrove swamps, tidal channels, tidal flats, bays, beaches, spits and bars are the depositional environments on the coast where heavy mineral assemblages are found in the sediments. Heavy mineral assemblages on this coast usually contain ilmenite, magnetite, kyanite, tourmaline, rutile, zircon, augite, hornblende and olivine, especially in scattered manner in the medium to small size pocket beaches and spits. Kalbadevi, Ratnagiri, Mirya, Golap, Pavas, Ambolgad, Jaitapur bay, are the places where these placer minerals are reported (Fig. 27).

**Purnagad Creek** is a tidal mouth of Machkundi River. The tidal water ingress into the river is up to a distance of 30 km inland, although normally the lower 800 m of the streams are tidal with placer deposits, especially the ilmenite. The tidal mouth Machkundi River has narrowed significantly around Gaokhadi. The creek and the lower reaches of Machkundi River are surrounded by lateritic plateaus. River banks are steep and the river presents the appearance of an entrenched valley. Small streams joining the creek originate on the nearby lateritic plateau, where the long process of weathering and denudation has resulted in re-lateritisation. Many stream beds are covered with lateritic gravels and boulders.

Sea cliffs at Ambolgad are 5-8 m high and are essentially found on the seaward margin of a wide lateritic headland plateau (Fig. 28). The deep cracks produced on the plateau suggest marginal disintegration and retreat of the plateau margin (Fig. 29).

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**Fig. 27. Road to Ambolgad.**

**Fig. 28. Sea cliffs and shore platforms at Ambolgad.**

**Fig. 29. Marginal back-wearing of a lateritic cliff at Ambolgad.**
Day 4
Ratnagiri to Malvan
Stay at Malvan.

Malvan is located at a distance of 143 km from Ratnagiri by coastal highway that joins Mumbai with Panaji.

Beyond Ratnagiri, as one drives southwards towards Malvan via Ambolgad and Kunkeshwar Shore Temple, one passes through a quiet and lush green countryside with a typical rural landscape that includes small streams, vast rolling plains, as well as the backwaters and idyllic beaches before one reaches Malvan via Ambolgad, Kunkeshwar (Shore Temple). Malvan and small settlements like Tarkarli and Deobag are renowned for coastal cuisine, local handicraft, old temples, water sports and scuba diving (Fig. 30). Other sites of interest along this stretch include Vijaydurg, Kunkeshwar, Sindhudurg Fort and Devbag.

Vijaydurg Fort, the oldest fort on the Sindhudurg coast, was constructed during 1193-1205 and restructured by Chhatrapati Shivaji Maharaj. Recent oceanographic evidence supports a traditional view that an undersea wall exists here, constructed out at sea at a depth of 8–10 m. Made of laterite, the wall is estimated to be 122 m long, 3 m high and 7 m wide (Fig. 31).

On August 18, 1868, Vijaydurg lay in the path of a solar eclipse. The English Astronomer Norman Lockyer, founder of the journal Nature, discovered the element Helium while observing the solar prominences from Vijaydurg fort during that eclipse. The place from where Lockyer made his scientific observation is marked on the Fort.

Kunkeshwar on the shore is better known for a temple dedicated to Lord Shiva. Lateritic sea cliff, sandy beach and a wide dune zone are the notable features in this area.

Sindhudurg Fort is on a small island in the Arabian Sea, just off the coast of Malvan. It is a protected monument. This massive fort was constructed in the year 1656 by Chhatrapati
Shivaji Maharaj during the peak of his Maratha Empire. The main object was to counter the rising influence of foreign colonizers (e.g., the English, Dutch, French and Portuguese merchants) and to curb the rise of Siddi clan of Janjira. The construction was supervised by Hiroji Indulkar.

Deobag, about 16 km south of Malwan, is a 6 km long sand bar on the coast (Fig. 32). The sand bar is connected to the mainland near Tarkarli, and its southern tip ends abruptly in the sea near Mobar. The eastern edge of the bar is bordered by tidal stretch of River Karli. The western margin faces the Arabian Sea. The tidal range along the bar is 2.6 m at spring and 1.8 m at neap. The dominant wave height is 1.8 m and the maximum surge level is 4.6 m.

Storm surges occur frequently in this area, especially coinciding with the onshore southwest monsoon winds. The atmospheric pressure anomalies and temperature changes cause a rise and fall of sea level by about 30 cm every year. Episodic inundation due to storm surges during every monsoon since the last few years has been recorded.

Redistribution of sandy material inside the creek is very striking here (Fig. 33). The progressive landward movement of waterfront towards Devbag settlement and the inundation of about a 100-m wide stretch of the upper part of the sand bar has become an annual feature. Severe breaching and erosion of shorefront has been reported in the years 1952, 1956, 1980, 1997, 1999, 2000, 2005, 2012 and 2016.
Day 5
Malvan to Panaji (Goa)
Depart from Panaji.

The last day of the field trip will start from Malvan and end at Panaji in Goa, after traversing the coastal stretch of North Goa between Keri and Calangute (Fig. 34).

Like all estuarine mouths on the Konkan coast, the estuary of the Terekhol River at Keri is broad when compared with the width inland. The estuary is blocked by a spit that extends northward and restricts the flow of water at the mouth (Fig. 35). Just to the east of this spit is the ferry point at Keri where one has to cross the River Terekhol before entering the state of Goa.

At Keri the waves from the sea enter the estuary from two directions. First they come in through the mouth from the river and travel along it inland. The other set of waves first strikes the headland at the north, then gets deflected by it and enters the mouth.

North Goa Coast: The beach at Keri is quite steep, composed mainly of fine sand. As one travels along the sea face to the south (Fig. 36) the beach becomes broader. The wind and
wave action continuously rework the beach sand, forming many micro-features on the beach. The coast here is also characterized by stable sand dunes in their pristine forms. The fore- and mid-dunes are not very prominent. The backshore is well protected by a thick plantation of Casuarina plants. The creek is characterized by many sand lenses, sand bars, tidal mud flats and mangrove swamps.

At Arambol (15.7° N / 73.7° E) the sandy shore has very well developed fore- and mid-dunes, which are well covered with Spinifex plants. A sweet-water body is located adjacent to the beach at the base of the hill. Mandrem beach in this sector has long stretches of sandy shore with mature sand dunes that are well-protected by vegetation. Apart from the mature backshore dunes, one can also see here the embryo dunes, as well as the fore- and mid-dunes.

Ashvem (15.6° N / 73.7° E), slightly to the south, has a mixed shore with sandy and rocky beaches. The coastal dunes are well protected by plantation.

Morjim preserves a good sandy shore with well-developed dune system. The backshore dunes are not well stabilized, but the embryo dunes and the fore and mid dunes are relatively better preserved.

South of Chapora Fort, and especially at Vagator, low sand dunes are common over a limited stretch. It comprises of a rocky coast with some sandy pockets. Similarly, at Anjuna, there are extensive sand dunes covered by vegetation. Many dunes are also degraded. One can clearly see many disturbed chaotic strandlines at several places along the shoreline in this sector.

Fig. 36. Map of the beaches to the south of Keri.
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Indian Institute of Geomorphologists
B6: Geomorphological Field Guide Book on
SEMI-ARID GUJARAT ALLUVIAL PLAIN

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Guide Book on Semi-arid Gujarat Alluvial Plain (Edited by Amal
Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the USGS site). Boundaries are approximate.
## Itinerary

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The state of Gujarat, located astride the Tropic of Cancer, and to the south of the Thar Desert of Indian subcontinent, forms an important part of the drylands of western India. The climate of the state is dominantly semi-arid, but the northernmost part in Kachchh and Banaskantha has an arid climate, while the southernmost part experiences a sub-humid climate. Winter is mild, pleasant and dry in the state. The average daytime temperatures is around 29°C (84°F) and night temperature is about 12°C (54°F), with sunny days and clear nights. Summer is extremely hot and dry when day temperatures usually rises to 45°C (120°F), while night temperature reaches about 30°C (86°F). In the weeks leading to the arrival of the southwest monsoon rains by mid-June, the high temperature gets associated with high humidity, making the condition very oppressive. As the rains arrive the temperature drops to below 35°C. Rainy season continues till the end of September, and often causes flood in many areas. The rest of the months receive almost no rainfall.

Physiographically, Gujarat can be divided into the following three well-defined zones: Mainland Gujarat, Saurashtra, and Kachchh peninsula (Fig. 2). These three zones correspond well with the three distinct tectonic provinces of western India (Fig. 3). The geological set up of the state is a result of complex interaction between tectonism and sea level changes during the Cenozoic. The basic framework was formed due to sequential fragmentation of the western continental margin of the Indian plate during Late Mesozoic, as it collided with the Eurasian plate in the north (Biswas, 1987). The break up of the margin resulted in the formation of the Kachchh, Cambay and Narmada rift basins along the Satpura, Dharwar and

![Fig. 2. Physiographic zones in Gujarat state and sites to be visited.](image)
Narmada trends (Biswas, 1987). These basins have been the major depo-centers of western India since then and furnish classical examples of sedimentation in tectonically controlled environment. While a major part of Tertiary sediments in these basins is of marine origin, the Quaternary sedimentation has been largely fluvial (Merh, 1993).

Fig. 3.
(a) Map of Gujarat showing the nature of tectonic movements during Quaternary.
(b) N-S cross section across the Gujarat alluvial plain showing the variable thickness of Quaternary sediments (after Maurya et al., 1995).
Mainland Gujarat can be divided into four broad geomorphic zones: the eastern upland zone, the shallow buried pediment zone, the alluvial zone and the coastal zone (Maurya et al., 2000). The flat alluvial plain, called the Gujarat Alluvial Plain, is bordered by the Aravalli ranges and the Trappean highlands to its east (Fig. 3a), and occupies a major part of Mainland Gujarat. Its subsurface cross section brings out the influence of tectonic framework of the Cambay and the Narmada basins, and their various tectonic blocks, on Quaternary sedimentation within the plain (Fig. 3b). The basin is composed of a series of horsts and grabens from the Tertiary period, which are subjected to periodic uplifts and subsidence, but overall the basin is subsiding. The plain shows a gentle slope towards SW.

Fluvial system

The landscape of the area has evolved due to tectonic activities and other palaeo-environmental changes during the late Quaternary period (Maurya et al., 2000; Chamyal et al., 2003). The streams of Mainland Gujarat originate in the eastern highlands and debouch into the Gulf of Cambay. The Sabarmati, the Mahi and the Narmada are the major rivers draining the alluvial plains (Fig. 4). All the rivers of the alluvial plains are characterised by gorge-like valleys with 30-50 m high vertical cliffy banks, associated deep ravines, presence of tributaries on one bank only, deeply entrenched meanders, and slope-deviatory approach of several rivers. All these features suggest an influence of tectonism.

Lineament analysis has revealed a strong control of tectonic elements in the drainage configuration (Maurya et al., 2000). The lineaments correspond to three major structural trends, NE-SW, ENE-WSW and NNW-SSE, which parallel the Aravalli, Satpura and Dharwar regional trends, respectively (Fig. 4). The Dharwar trend is found to dominate in the northern and central part, where the Aravalli trend is present as the second major trend. The Satpura trend dominates the southern part. The N-S and NNW-SSE lineaments seem to reflect the basin configuration, while drainage courses of the area follow NE-SW and NNE-SSW lineaments (Maurya et al., 2000).

The NNW-SSE and ENE-WSW lineaments (Fig. 4) correlate well with the subsurface intra-basin horsts and grabens in the northern alluvial plains (Maurya et al., 2000). The ENE-WSW to E-W trend suggests the subsurface continuation of the Aravallis. The area south of Mehsana and up to Sabarmati River is devoid of basement highs, which diverts the streams like the Sabarmati River to flow towards the south. To the south of Sabarmati River, a NE-SW to NNE-SSW subsidiary trend is seen in addition to the dominant trend. The eastern margin fault is represented by a series of sub-
parallel en-echelon lineaments trending in N-S and NNW-SSE directions (Fig. 4). The lineament density on the eastern margin is higher as compared to that on the western margin. Near Narmada River the NE-SW lineament is replaced by a ENE-WSW lineament, suggesting an influence of the Narmada-Son Fault (Fig. 4). South of the Mahi River a major lineament trending NNE-SSW controls the extent of ravines along that river, as also the course of the Vishwamitri River. An E-W trending lineament along the Mahi estuary marks the Mahisagar Fault in the subsurface.

The lineament rosettes for the northern, central and southern alluvial plains show a change from N-S orientation in the northern plains to ENE-WSW in the southern plains (Fig. 4 A, B, C). In the northern plains, the N-S Cambay basin trend is dominant whereas in the central plains, a gradual swing towards the east is observed because of the increasing influence of the NE-SW Aravalli trend. In this part, the NNW-SSE and NNE-SSW trends dominate. In the southern plains, the major lineaments trend ENE-WSW, parallel to the Narmada trend (Maurya et al., 2000). Lineaments parallel to the Cambay trend are less common.

As suggested above, the drainage architecture of the Gujarat Alluvial Plain reveals a strong structural control (Fig. 5), with excellent correlation with the subsurface structural highs and faults (Maurya et al., 2000). Several areas are devoid of significant drainage lines, viz. to the west of the Sabarmati River, between the lower courses of the Sabarmati and the Mahi rivers, in the lower courses of the Mahi and the Dhadhar rivers, to the west of the lower course of the Orsang River, and to the south of Narmada River (Fig. 5). Such areas correspond well with the subsurface structural highs (Maurya et al., 2000). Several anticlines are present to the south of the Narmada River, causing a northward shift of the course of the river (Fig. 5);
Maurya et al., 2000; Chamyal et al., 2002). The courses of the Sabarmati, the Mahi and the Orsang do not follow the SW regional slope of the plains. According to Maurya et al. (2000), the N-S to NNE-SSW segments of these three rivers appear to have captured the E-W to ENE-W SW courses of their tributaries which follow the regional slope. The Sabarmati has captured the course of the Vatrak, while the Mahi has captured the course of the Mini, Mesri and Goma rivers, and the Orsang has captured the course of the E-W flowing Heran and Unch rivers. Maurya et al. (2000) also envisaged a phase of drainage realignment during which large-scale river capture took place by the structurally-controlled major rivers. Some rivers, however, show a tendency to flow along or parallel to the basin axis, but an axial drainage consistent with the basin axis is absent in the plains.

Three distinct geomorphic surfaces could be noticed in the landscape in and around the major river valleys of Mainland Gujarat (Maurya et al. 2000). These are: the alluvial plain (S1), the ravine surface (S2) comprising Late Pleistocene sediments, and the Mid-Late Holocene valley fill terrace (S3). The sediments comprising these surfaces have great bearing on the evolutionary history of Mainland Gujarat during the Late Pleistocene and the Holocene.
Regional Stratigraphy of the Exposed Quaternary Sediments

The 30-40 m high alluvial cliffs all along the valleys of the Mahi, the Sabarmati and the lower part of the Namada expose late Pleistocene sediments dating back to ~125 ka BP (Maurya et al., 2000). The exposed succession begins with fine clayey silt that becomes fluvio-marine silty clay in areas proximal to the coast (Fig. 6). This is overlain by cross-stratified gravel. A silty sand horizon with bedded calcrete overlies the gravel, which is overlain either by gritty sand or assorted gravels. Upward in the sequence lies the pedogenically modified silty sand. The uppermost pedogenically modified horizon shows reddening (red soil) that has been used as inter-basin stratigraphic marker. With exception of a few localities where the red soil is overlain by cross-stratified gravel, in majority of cases a weak to moderate pedogenically modified silty sand horizon overlies the red soil (Fig. 6). This horizon grades either into fluvio-aeolian sand or fining upward channel sand. The sequence above red soil has been designated as the upper fluvial sequence (Srivastava et al., 2001; Juyal et al., 2006). This is overlain by aeolian sand that constitutes the topmost litho-unit in the region.

Presence of fluvio-aeolian sediments suggests that the transition from fluvial to aeolian phase was gradual. After ~25 ka, the fluvial regime began to dwindle as indicated by the fining upward channel sand. The establishment of aeolian sedimentation followed this. Since the controlling factors for aeolian sedimentation are the wind strength and the moisture/vegetation cover, it is suggested that aeolian activity began with the weakening of southwest monsoon around LGM (~ 20 ka). In the dry sub-humid Orsang basin, aeolian sedimentation terminated after the LGM, but in the semi-arid Mahi basin it continued till around 11 ka. Further north, in the Sabarmati basin, aeolian sedimentation continued till 5 ka (Juyal et al., 2003). This shows a gradual northward propagation of aeolian activity, and suggests a moisture-vegetation control on the aeolian dynamics (Juyal et al., 2003).

Fig. 6.
Exposed late Pleistocene stratigraphy along the Gujarat streams.
Socio-economic Aspects

Population Density
Gujarat is one of the most industrialized states of India and thus attracts people from India both in terms of investment and jobs. From 50,671,017 in 2001, the population of Gujarat has gone to 60,383,628 in 2011. In terms of population, Ahmedabad is the largest city of Gujarat with 6.2 million people living here. Surat and Vadodara are other two major cities with high number of urban population residing here. Rajkot is the fourth largest city of Gujarat with population of 1.50 million. The cities like Bhavnagar, Bhuj, Junagadh and Jamnagar constitutes a large number of urban populations in Gujarat. Population in Gujarat is growing at an annual growth rate of 1.9 percent.

Gujarat has also shown an increase in its literacy rate by 10 percent in this decade. Currently it stands at 79.31 percent as compared to last census (2001) figures of 69.14 percent. Better education facilities by the state government have proved a vital role in improving overall literacy rate of Gujarat. According to latest Census of 2011, Male Literacy rate in Gujarat stands at 87.23 percent while female literacy rate is 70.73 percent.

Agriculture
Gujarat is the main producer of tobacco, cotton, and groundnuts in India. Other major crops produced are rice, wheat, jowar, bajra, maize, tur, and gram. Gujarat has an agricultural economy; the total crop area amounts to more than one-half of the total land area. Animal husbandry and dairying have played a vital role in the rural economy of Gujarat. Dairy farming, primarily concerned with milk production, functions on a cooperative basis and has more than a million members. Gujarat is the largest processor of milk in India. Amul milk co-operative federation products are well known all over India and is Asia's biggest dairy. Among livestock raised are buffalo and other cattle, sheep, and goats. As per the livestock census, there were 20.97 million livestock in Gujarat state in 1997. As per the estimates of the survey of major livestock products, during the year 2002–03 the Gujarat produced 6.09 million tonnes of milk, 385 million eggs and 2.71 million kg of wool. Gujarat also contributes inputs to industries like textiles, oil and soap.
Vadodara - Educational and Cultural Heritage
Sir Sayaji Rao Gaekwad III, the late ruler of Vadodara had a dream to make Vadodara an educational, industrial and commercial centre. He ensured that his dream came true. The city of Vadodara has a long history. The first noted history of the city was of the early traders who settled here in 812 AD. The city afterwards came under the Gupta dynasty, and then under the Chalukya dynasty and the Solanki dynasty. It then was captured by the Delhi Sultans, and subsequently by the Mughals. Since the city was a known seat of trade and commerce with international connectivity, Vadodara always remained a prized possession of the rulers of India. During the Mughal Period the Marathas of the Deccan region became more powerful, and eventually they took control of Vadodara and its large hinterland. Vadodara then became the capital of the Maratha Gaekwad, and remained so till independence of India in 1947.

Vadodara is now the third largest state in Gujarat, and is famous for its rich culture and heritage. The inhabitants love to tell the visitors that their city is a 'Sanskari Nagari', i.e., a 'cultured city'. Diwali, Uttrarayan, Holi, Eid, Gudi Padwa and Ganesh Chaturthi are celebrated here with great fervour. Vadodara is also famous for ‘Garba’ dance, which is performed all across Gujarat during the nine-day Durga Puja festival, the ‘Nava-Ratri’ celebration. The city has several places of tourist interest, which include the Laxmi Vilas Palace, Baps Swaminarayan temple, EME Temple, Baroda Museum and Picture Gallery, Sayaji Baug, etc. Vadodara is also known for its art and architecture. Under the patronage of the royal Gaekwad family since 19th Century, Vadodara became a hub of art and architecture. The city is also known as the 'Kala Nagari'.

Ahmedabad - Educational and Cultural Heritage
Ahmedabad, once termed as India's Manchester, is one of the oldest cities in India. The city now dreams to get recognition as one of the World's Heritage Cities. It has been witness to some of India's historic events. It was from this city that Mahatma Gandhi started his Dandi March. Ahmedabad is a city that boasts of a vibrant walled city which has generated much interest all over the world. It's a city where history gently rubs its shoulders with modernity.

Apart from the Indo-Islamic architecture for which Ahmedabad is quite well known, there are almost 100 Jain temples in the old city, some of which are architectural wonders from Medieval Gujarat. The old city within the walls with designated gates (or the ‘Pols’) has many traditional houses, which capture the essence of community living, and are unique to Ahmedabad. So are the ‘chabutras’, or the open spaces in between a cluster of houses, or even a large courtyard in a building complex, which is designated for feeding the birds. Such traditional systems throw light on the peaceful
living style of the inhabitants of the city. Ahmedabad has played a vital role in the independence movement of the country. Unlike many other glorious cities across the globe that have lost their relevance and distinct character, Ahmedabad has kept its past alive and looks forward to a promising future. Many other Indian cities have taken lessons from Ahmedabad on conservation of heritage. The city also boasts of a Heritage Walk which takes the visitors through the lanes and by-lanes of history. Architects, planners and heritage conservationists agree that Ahmedabad is a "living heritage city" where the walled city planning system is based on the ancient traditional "Vastu" principles. The sharing of community spaces and resources such as water and building structure, techniques and materials, offers social security and self-sufficiency to the ‘pol’ inhabitants.
B. DESCRIPTION OF THE FIELD SITES

Day 1: 12/11/2017
New Delhi to Vadodara by Flight
Discussion on the logistics
Stay at Vadodara.

On the first day, the delegates will arrive from New Delhi to Vadodara by flight. The programme for the day includes an informal gathering for a briefing on the day-wise schedule of the field trip, as well as for a discussion on the general geological and geomorphological characteristics of the Gujarat Alluvial Plain.

Day 2: 13/11/2017
Vadodara to Rayka, Kothiyakhad, Mujpur, Dabka in Mahi River basin and back
Stay at Vadodara.

It is proposed to begin the field trip in Gujarat Alluvial Plain with an excursion to the Mahi River basin. To appreciate the landscape better and to understand the geomorphology of the area, we first provide a short review of the tectono-morphic setting of the basin and its importance in the late Quaternary evolutionary history of the landforms.

Geomorphology and Late Quaternary Sequences of Mahi River Basin

The Mahi River basin is the third largest river basin in Gujarat, after the Narmada and the Tapi River basins. The Mahi River originates in the Aravalli hills and flows along the eastern flank of the Cambay Graben, which is an intra-cratonic rift graben (Biswas, 1987). It then flows through its alluvial plain before debouching into the Gulf of Cambay. The East Cambay Basin Margin Fault (ECBMF) cuts across the Mahi River, as indicated by a change in orientation of the river (Maurya et al., 1997a). Several N–S and NNW–SSE trending fractures that developed parallel to the ECBMF have strongly influenced the drainage pattern in the basin (Maurya et al. 1997a; Pant and Chamyal, 1990). Thus, whenever the Mahi approaches a lineament it deviates from its NE–SW path to take a NNE–SSW course. Subsurface data indicate the presence of pre-existing step faults parallel to the ECBMF that acted as the depo-centre for late Pleistocene sedimentation (Maurya et al. 1995; 1997a). The Mahi basin lies in a horst segment, which has more than 300 m of Quaternary sediments overlying the Tertiary rocks (Maurya et al. 1995). The geomorphic features of the basin indicate a complex interplay of tectonism and base level changes in its evolution (Maurya et al. 1997a; Pant and Chamyal, 1990). Two distinct geomorphic zones are identified here.
The first zone, identified as the rocky upland zone, is characterized by high, steep, rocky hill slopes with deep and narrow stream valleys having steep longitudinal profiles. This zone has been rejuvenated during the Quaternary period (Sen and Sen, 1983; Ahmad, 1986). The second zone is the alluvial zone, where the Pleistocene-Holocene alleviation took place. The landscape here is dominated by wide valleys, but also includes extensive badlands that suggest active denudational processes related to Holocene tectonic uplift (Raj et al. 1999). The Mahi River has carved out a conspicuous entrenched meandering course across the alluvial plain. Two distinct land surfaces, an older $S_1$ and a younger $S_2$, can be demarcated from the different geomorphic features along the Mahi River (Maurya et al., 1997b). The $S_1$ is an old, pre-Holocene surface, and is paired, highly eroded and extensively dissected, comprising of sand, silt and gravel, mainly of fluvial and aeolian origins. The $S_2$ is the younger Holocene surface, which occurs as unpaired elevated terraces, comprising of two lithofacies: (a) the tidal estuarine mud and sand, and (b) the fine to medium sand of mixed environment. Two phases of tectonic uplift and fluctuating sea-level have helped in shaping the landscape of the lower Mahi valley (Maurya et al., 1997b).

An observation of the $S_2$ surface shows that the sequence commences with the deposition of marine clay (Raj et al., 1998), with evidence of intense pedogenesis (Khadkikar et al., 1998). It is overlain by a planar cross-stratified gravel bed (Gravel-1). This is succeeded by a sandy layer with mud drapes and bedded calcrites. Trough cross-bedded gravel (Gravel-2) overlies this, which in turn is overlain by two to three pedogenised horizons, the uppermost being red in color (red soil). The red soil is overlain by medium to fine-grained fluvial sand that becomes fluvio-aeolian in character in the upper part. The aeolian sand sheet finally blankets the succession (Fig. 7). At Rayka, the aeolian sand sheet directly overlies the red soil. However, recent investigations in the lower reaches of the Mahi basin indicated that a renewed phase of fluvial aggradation followed the development of red soil. This event has been

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**Fig. 7.**

Lithostratigraphic succession exposed at Rayka with BGSL ages (after Juyal et al., 2000).
designated as the upper fluvial sequence (Srivastava et al., 2001, Juyal et al., 2006), which gradually merges upwards into the aeolian sediments.

Proximity of the Mahi basin to the Gulf of Cambay and presence of marine clays at the base of the exposed sections suggest eustatic control on sedimentation. The overlying fluvial aggradation was consequent to base level changes following marine regression. During this phase, the river could erode and transport sediments from poorly vegetated catchment (Graf, 1988). Presence of basalt and carbonate concretions in Gravel-1 indicates poorly vegetated source (proximal catchment). The silty sand with bedded calcretes overlying Gravel-1 suggests cohesive banks and persistent flow (sinuous stream) with periods of dryness resulting in the formation of bedded calcretes (McCarthy and Metcalf, 1990). Dominance of poorly-sorted clasts of calcrete, quartzite and basalt in Gravel-2 indicates substantial flow intensities. Rolled carbonate nodules further indicate the ability of flow to erode pre-existing alluvial carbonate under frequent channel migration. The textural evidences suggest the existence of ephemeral fluvial system during the deposition of Gravel-2. Fine sand, silt and clay that have been pedogenised, dominate the overlying sediments. These form laterally extensive sand sheets. Higher concentration of silt indicates that deposition occurred away from the main channel on the flood plain by the meandering stream (Juyal et al., 2000). Presence of pedogenic horizons suggests periods of alluviation, followed by prolonged periods of pedogenesis. Out of the three horizons, the uppermost is red in colour, whereas the lower two are grey in colour. Generally, the red soils develop on better drained sites, reflecting higher elevation and/or more permeable parent material, whereas the grey flood plain soils are formed in poorly drained areas with less permeable material (Kraus, 1997).

Following the development of red soil, climate temporarily reverted back to drier conditions as indicated by the overlying trough cross-stratified sandy gravel. However, this event was short-lived and localized. Discrete occurrence of planar and cross-stratified gravel dominated by poorly sorted clasts of basalt, quartzite and calcrite at Dodka, Jaspur and Sultanpur, suggests sudden increase in sediment supply. This could happen in arid and semi-arid environment where episodic storm surge events are common, during which rivers are capable of eroding and transporting sediments from poorly vegetated catchment (Graf, 1988). This gives rise to braided channel system having typically large width to depth ratio in which the number of individual channels can vary from 1 to more than 20 (Thornes, 1994). In a rare event the river bed is completely occupied. However, in a given time the distributary channels carry water and are known for frequent migrations that lead to bank erosion. In view of limited extent of such features, it can be suggested that the event was short-lived and local in nature.
A persistent fluvial regime reappears in the basin with the deposition of fine silty sand, usually overlying the red soil. Distinct fluvial signatures are preserved in the form of current ripple laminations and mud balls, suggesting prevalence of a low-energy meandering river system. The deposits are typical of flood plain fine facies of Miall (1996), representing the sedimentation in a flood plain regime (Willis and Behrensmeyer, 1994). These sediments are at times associated with the bedded calcrite at places like Jaspur and Dahewan. Bedded calcrite formation is usually related to the groundwater fluctuation in a riverine playa environment (Goudie, 1983), thus suggesting its deposition proximal to a channel. It has been suggested that in semi-arid areas the flood plains are most conducive locations for the development of bedded calcretes where groundwater remains close to the surface, ensures high evaporation, and facilitates calcrite development (McCarthy and Metcalf, 1990). A vertical aggradation of this facies, ranging in thickness from 2-10 m, suggests that the deposition was facilitated under a persistent flow regime under a well-defined channel (e.g. meandering course) with periodic over-spilling of silty sand on to the adjacent floodplains. Evidence of moderate pedogenesis associated with these sediments suggests phases of non-deposition when the channel responsible for the flood plain aggradation migrated laterally. Such channel migration occurs under changing water budget (both increasing and decreasing). In either situation, river tends to abandon the old course and occupies the new one. This leads to the exposure of the flood plain sediments to sub-aerial weathering and the development of flood plain soils (Kraus and Aslan, 1993). It is evident that the sediments above the red soil were deposited under improved moisture availability. The overlying aeolian sand shows gradational contact with the underlying fluvial horizon. This indicates initiation of drier climatic condition, which could be associated with enhanced wind activity in the region.

Juyal et al. (2000) provided the chronology for the exposed Late Quaternary sequence at Rayka that is considered to be the type locality in the Mahi basin. The basal marine clay was assigned the Marine Isotopic Stage-5 (MIS-5). Gravel-1 and 2 were deposited between the MIS-5 and 74 ka and the silty sand with intercalated pedogenised horizons were formed between 74 ka and 40 ka. However, recent chronometric data based on Quartz extract on red soil at Jaspur suggest that the sequence overlying the red soil could have developed between 68 ka and 50 ka. Thus, the earlier age of 40±10 ka on red soil obtained on feldspar mineral at Rayka probably suggests an age underestimation due to fading, a phenomenon associated with feldspar dating (Juyal et al., 2000). Since luminescence dating gives the sediment deposition ages, hence it can be inferred that red soil development postdates 68 ka (age of red soil sediment) and pre-dates 50 ka (age of the overlying fluvial sand), and probably represents the Marine Isotopic Stage-4.
The overlying fluvial and fluvio-aeolian sediments (upper fluvial sequence) are bracketed between 50±8 and 34±3 ka (MIS-3). Presence of bedded calcretes in the upper fluvial sequence dated to MIS-3 indicates that fluvial activity was not monotonous but punctuated by fluctuating hydraulic discharge. Towards the upper part, dominance of very fine sand indicates that there was a subordinate aeolian component getting admixed with the weak fluvial regime. Finally, the drier conditions set in around 30 ka, as indicated by the initiation of aeolian sedimentation.

**Stop 1: Rayka Section**

The Rayka section is located 20 km NW of Baroda on the eastern flank (left bank) of Mahi River. It exposes a 40 m high alluvial cliff. The section has been considered as a type section and documents a sequence of the palaeoclimatic variation over the past ~125 ka (Fig. 7). The exposed succession shows two distinct phases of fluvial aggradation. The earliest is located between Gravel-1 and Gravel-2 in the form of sandy calcareous (62% sand) unit. This is followed by the second phase, which is represented by a sandy silt (59% sand) unit, intercalated with palaeosols lying above Gravel-2. The stratigraphic succession of the deposit commences with a clay bed containing shallow marine microfauna, which is overlain by planar cross-stratified Gravel-1. The clay has yielded fairly rich assemblage of foraminiferids, comprising benthic foraminiferids (Rachna Raj et al., 1998) like Pararotalia sp., Brizalina spp., Nonion spp., Cibicides spp., Florilus spp., Ammonia spp., and three species of planktonic foraminiferids, viz., Turborotalia sp., Globigerina bulloides (Parker, Jones and Brady) and Globigerinoides ruber (d’Orbigny). On the basis of the foraminiferids, it has been concluded that the formation was deposited in an estuarine to marginal marine environment, having low salinity due to influx of fresh water during Late Pleistocene. The marine clay is yellowish brown (10 YR 5/4) to brown (7.5 YR 5/4) and is highly pedogenised. The exposed thickness of the unit ranges from 0.5m to 3.0 m, but extends to a depth of 25 m below mean sea level at Rayka (Murthy, 1975). The unit shows intense fracturing with intersects, giving rise to subangular cohesive blocky aggregates, as also continuous concave upward planes, which can be interpreted as pseudo-anticlines (Fig. 8). Calcium carbonate is dispersed irregularly.
throughout the clays, both as nodules and tubes (*Fig. 8*). The clay mineral assemblage (Malik et al., 1999) is dominated by a very high percentage of smectite (montmorillonite), with subordinate quantities of illite and kaolinite. Presence of shallow marine foraminifera in the clays suggests that they were deposited during a high-sea strand corresponding to a pluvial climate.

The cross-bedded gravel that overlies the marine clay with an erosional contact indicates initiation of fluvial activity. Well-developed 2-3 m thick planar-cross stratification in the gravels, comprised of basalt fragments and carbonate nodules, indicate proximal source. Planar cross-stratification (1 m) is commonly associated with ephemeral flow and is often formed by an advancing channel bar. The presence of associated clay drapes indicates the recession of the flood peaks during which clay particles settle out. Thus, the Gravel-1 was perhaps deposited during the peak flood events when large volumes of wash load and bed load were eroded from poorly vegetated slopes.

This unit is overlain by laminated sandy silt with carbonates in discrete bands or as irregular nodules. Nearly 50 such layers are recorded, which occur at regular intervals. The composite thickness of these laterally traceable layers varies between 3 and 5 m. No significant pedogenesis has been found to be associated with these layers, which could be due to syn-depositional tectonism, as indicated by soft-sediment deformation structures (Maurya et al., 1997; Jain et al., 1998). Textural characteristics and consistency in the appearance of the individual layers that are separated by the calcium carbonate bands indicate a calm water environment in the flood basin area. The individual layers are suggestive of repeated flood events along a possibly sinuous stream during a humid climate when banks with strongly cohesive and constant sediment supply possibly meant restricted vegetation cover in the catchment. In between the episodes of overbank sedimentation there were probably periods of aridity, which facilitated calcium carbonate precipitation.

The soft sediment deformational structures within the fine-grained silty sand show fold structures of intra-formational character. These in some cases extend up to 15 m. The geometric shapes of these folds vary from wide open folds to flexures and monoclines. The calcrete bands show well developed plunging folds, where the fold axis trends towards south with a plunge of 10-15°. The wave length of the fold varies from 1.5 m to 2.0 m with an amplitude of 0.5 m. The monocline shows an apparent steepening towards west, suggesting that the down-faulted block lies to the west. The smaller, closely-spaced minor faults within the strata are significant indicators of syn-depositional tectonism. In another study by Jain et al (1998) at Rayka, four NW-striking faults were mapped, having throws ranging from 1 m to more than 3 m. They
related the growth of folds in synchronous sediment units. They showed that a slump sheet moved tens of meters northeastward down the 0.7° dip slope of one tilt block during displacement on its bounding faults.

The silty sand horizon is overlain by a highly mottled and pedogenised mud. This shows well-developed vertisol characters such as desiccation cracks, drab halos and calcium carbonate root casts. The deposit is typical of a flood plain and seems to have been deposited during the final phase of flood events in isolated flood pools. Intensive fracturing, reflecting pedogenic activity, has given rise to sub-angular aggregates described as peds. Peds form through repeated expansion and shrinkage of clays, coupled with root activity of plants. Striations formed due to preferential orientation of clay minerals are found on the ped faces. Calcium carbonate nodules and tubes occur throughout. Vertical fissures form in response to extreme drying events when the soil starts cracking. Greenish grey drab haloes consist of a white carbonate-rich core, enveloped by greenish grey clays, gradually merging with the host clays.

The vertisol is overlain by a 1-2 m thick Gravel-2 with trough cross-stratification. It occurs as isolated bodies dominated by poorly-sorted clasts of calcrete, quartzite and basalt. A wedge-like geometry is seen where stratification planes of the gravel extend into the adjacent sand unit to form a large trough. The lower bounding surface is erosive with respect to the underlying mottled clays. The fore sets show normal grading and dip of 14°-25° due SW to SSW in the northern sections and SSE, SSW and W in the southern sections (Malik et al., 1999). Trough cross-stratification is usually formed by the downstream migration of trains of sinuous-crested mega dunes in a deep channel profile. These troughs show decreasing amplitude towards the top, suggesting a declining flow. Such poorly-sorted, relatively large clasts (~10 cm) are indicative of enhancement in the flow intensity due to the change in the stream gradient. The trough axes of the fore sets are indicative of the channel orientation with high angle of plane beds (16°-18°), suggesting their deposition as point bars. Rolled carbonate nodules indicate the ability of the flow to erode the stable surface in the upper alluvial plain. The lithofacies are a product of sedimentation under a high flow regime in developing channel bars (Miall, 1978, 1985; Todd and Went, 1991). Overall, the evidence suggests the existence of an ephemeral fluvial system.

Gravel-2 is overlain by thick (~10 m) alluvium, comprising fine sand, silt and clay which is intercalated with three weathered horizons, identified as palaeosols (Fig. 9). These deposits form laterally-extensive sheets of silty sand with pedogenic calcium carbonate nodules, dispersed in sub-parallel layers. Higher silt content indicates their deposition away from the main channel as a floodplain deposit by a stream that
had a consistent flow path. The presence of palaeosols indicates the episodic nature of deposition with each phase of alleviation, followed by a period of pedogenesis. These possibly were caused by channel avulsion in association with continued aggradation after the deposition of Gravel-2. Alternately, these reflect episodes of climate-induced flow regime changes. The temporary hiatuses, corresponding to the peodogenesis, could be due to waning flow or channel avulsion. The three palaeosols show well-developed thick B horizon and complete absence of the A horizon. Each soil is somewhat different in colour. The lower and middle palaeosols are yellowish brown to grey in colour (10YR 5/4 and 10YR 7/4). Small sub-millimeter diameter buried root-channels, lined by carbonates, are seen. These soils generally are less calcified as compared to the overlying red (rubified) soil. Carbonate nodules occurring within the soil profile are orthic and irregular in morphology, and are on an average 1-2 cm in size. The granulometric analysis shows mean average grain size ranging between 3.33 and 3.96 Ø. It comprises of an average 48-62% of sand, 28-36% of silt and 8-16% of clay, and is moderately well sorted. The clay mineral assemblage shows high concentration of montmorillonite with subordinate amount of kaolinite and illite. On the basis of granulometric analysis these soils can be categorized as sandy loam. The brown coloured horizons, which show higher concentration of clay as compared to the overlying rubified soil, suggest clay illuviation and soil formation, evidenced by the presence of root channels, development of aggregates (peds) and minor calcareous nodules. These features indicate that the soil is moderately developed. The presence of montmorillonite, along with subordinate kaolinite and illite, suggests a provenance similar to the red soil. The relatively higher content of kaolinite indicates a wetter climatic phase with an annual precipitation of more than 900 mm (Weaver, 1989). This clay mineral forms in high-leaching conditions. However, the presence of calcrete nodules (though less profuse) in these profiles is attributed to subsequent drier time spans.
The upper soil, which has been used as a stratigraphic marker in the Mahi basin (Fig. 10), is yellowish red in colour (5YR 5/6). The granulometric analysis of this lithofacies shows mean grain size of 3.34-3.75 Ø. The sediments are composed of 54-74% sand, 20-28% silt and 6-18% clay, and are moderately well sorted. The clay mineral assemblage is dominated by smectite (montmorillonite) with subordinate amount of illite and kaolinite. Hematite is observed in traces. On the basis of granulometric analysis this soil may be categorized as sandy loam. The undulating nature of the upper contact suggests a subdued palaeo-topography. Pedogenesis is indicated by clay concentration in the soil profile. The higher concentration of smectite (montmorillonite) along with subordinate amount of illite, kaolinite and hematite (in trace amounts) suggests that the clay minerals were derived from sediments containing ferromagnesian minerals, along with potash and sodic feldspars and micas (Weaver, 1989). This is also supported by the presence of basalt granules in the host sediments, the weathering of which led to the above mentioned newly formed clays, mainly smectite (montmorillonite). Presence of hematite in trace amounts may be because of lack of crystallinity of this mineral that was responsible for the coloration of the soil horizon (Pye, 1983). The carbonate nodules accumulated at the base of the soil profile forming a distinct zone, with sharp boundaries not connected to each other. These characters point to the nodules as being pedogenic calcretes, and their concentration in the lower part of the unit suggests that these were related to the weathering profile. The palaeo-precipitation values calculated using the equation given by Retallack et al. (1990) gives values of around 2000 mm for a depth of 350 cm. But as such values are unlikely for calcic soil, it is suggested that the red soil is actually a pedocomplex (cumulative soil) and spans a considerable period of time. The uppermost alluvial units are capped by fine aeolian sand and silt indicating the onset of aridity in the region (Fig. 10).
Stop 2: Kothiyakhad Section

This section is located in the estuarine zone of Mahi basin. The S2 surface at Kothiyakhad occurs as a 3-6 m high, flat terrace and has been mapped all along the lower Mahi basin as an unpaired terrace (Maurya et al., 1997a, 2000), whose clffy sections are cleaned by recent erosion (Fig. 11). Two major units identified in the successions are: (1) dark greyish brown clay with organic content and (2) greyish silty sand. These occur alternately with an erosional contact, and the base is unexposed. The clay units have yielded a good population of foraminiferids, whereas the silty-sand units have preserved fresh water ostracods. Radiocarbon dating of four organic-rich clay horizons at Kothiyakhad (Fig. 12) has provided dates of 3660+90, 3320+90, 2850+90 and 1760+80 yrs B.P. (Kusumgar et al., 1998). However, since the base of this sequence is not exposed, it is obvious that the actual deposition of the terrace sediments commenced prior to 3660+90 B.P. Radiocarbon dating of shells in the basal gravelly layer of a comparable fluvial terrace, overlying the basement rocks at

Fig. 11. Cliff section of a valley fill terrace on estuarine sediments at Kothiyakhad, showing alternate dark clays and silty sand.

Fig. 12. Litholog of the sediments exposed at Kothiyakhad with radiocarbon dates (after Kusumgar et al., 1998).
Vanoda in the pediment zone of Mahi River, has provided date of 6400+120 yr B.P. This suggests that the deposition of Holocene valley fill terraces was initiated within the river channels as the Holocene sea reached post-glacial high on the west coast at around 6000 B.P. (Maurya et al., 1997a, 2000; Hashimi et al., 1995). A total of 25 genera of foraminiferids were identified from the mud units of Kothiyakhad (Raj et al., 1998). Out of these, 23 are benthic comprising of Brizalina, Bulimina, Bolivina, Biloculina, Lagena, Triloculina, Pseudobulimina, Hopkinsina, Sagrina, Ammonia, Cibicides, Discorbid, Discorbinella, Florilus, Hastegerina, Melonis, Nonion, Nonionella, Pyrgo, Pyrgoella, Pararotalia, Parafissurina, Rosalina and few other Rotaliid. The two planktonic forms identified are Globigerinoides sacculifer (Brady), Globigerina bulloides (Parker, Jones and Brady), Globigerina ruber (d’Orbigny). The silty-sand units have yielded 3 genera of ostracods, namely Condona, Darwinula and Ilyocypris. Considering the morphology of benthic forms the 23 genera of foraminiferids were classified into two morpho-groups (Kusumgar et al., 1998): angular asymmetrical and rounded symmetrical.

In addition to the above, seismically-induced structures have also been observed in the Holocene terrace sediments at Kothiyakhad (Maurya et al., 1998, 2000). These include contorted laminations, load structures, convolutions, small-scale folds and syn-sedimentary micro-faults. Convolutions have been formed by tight folding of the beds, leading almost to the formation of pseudo-nodules. Downward-penetrating ‘sand-dyke-like features’ of fine sand into the underlying clay horizons is also observed due to seismic loading. The underlying horizons show effects of downward dragging, indicating that the dyke was forcibly intruded. Occurrence of load structures adjacent to these dykes and absence of any significant sediment cover suggest the role of seismic loading in the formation of these structures.

Soft-sediment deformational structures are important indicators of past seismic activity (Allen, 1975). The deformation took place due to liquefaction, which occurs during shaking of the sediments near the sediment-water interface, resulting in sagging or crumpling of the sediments (Maurya et al., 1998). Radiocarbon dating of organic-rich clay horizons (Kusumgar et al., 1998) from the Kothiyakhad section in the lower Mahi valley suggests that the deformation occurred during a late Holocene seismic event, which took place between 3320+90 and 2850+90 yrs. B.P. The Holocene tectonic activities thus played a role in the evolution of the Gujarat alluvial plains.
Stop 3: Mujpur Section
This section is located on the left bank of the Mahi River. The exposed succession is of about 6 m, showing alternate units of mud and silt. The base is not exposed and the 0.75-1.6 m thick laminated mud forms the base of the succession, which shows presence of sand lenses at places. The 0.75 m thick medium to fine grained sand that overlies this unit shows weak pedogenesis. This is overlain by 0.5 m thick horizontally-laminated mud. Alternating layers of silty-sand and mud of 1.2 m overlie it. The silty sand layer shows an average thickness of 20-30 cm, while the mud is 15-20 cm thick. This is overlain by 0.5 m thick laminated mud horizon, which is overlain by 1 m thick silty sand. Another 1 m thick laminated mud horizon overlies this silty sand. Finally, the succession is capped by a 0.5 m thick sand, showing well-developed soil unit. Soft-sediment deformational features can also be identified in Mujpur section (Maurya et al., 1998). These include injected liquefied sand, overturned folding, small-scale folds and syn-sedimentary micro-faults.

Stop 4: Dabka Section
This section is located in the present-day estuarine zone of the Mahi River. The cliff of 15 m is exposed on the left bank of the river, of which the basal 2 m succession is covered by scree material. The exposed succession shows well-developed 3 m thick medium to fine silty-sand horizon of red palaeosol (Fig. 10). The horizon is yellowish red (5YR 4/6) and is calcretised. The base of the horizon shows high concentration of calcrite nodule, ranging in size from 1.5 mm to 2.5 mm in diameter. The sediment size becomes coarser towards the top, along with the decreasing concentration of the calcrite nodules. In the upper part, the sediments are mainly silty-sand and show well-developed pedogenic features like buried rootlets, rhizo-concretions and burrows that are dark brown to black in colour. This is overlain by 5-6 m thick, horizontally-stratified silt horizon with sub-horizontal calcrite layers. The “loess-like” silt, which are 3 m thick, overlie this, and the succession is capped by 1 m thick dune sand (Fig. 10).
Day 3: 14/11/2017
Vadodara to Gamod, Tilakwada, Chandod, Phulwadi and back
Stay at Vadodara.

Some of the highly interesting landscape features in Gujarat Alluvial Plains occur in the lower Narmada River basin. These will be visited to appreciate their geomorphological characteristics and evolutionary traits. To appreciate the landscape better, a short review of the Quaternary landscape development in the basin is provided below.

**Geomorphology and Late Quaternary Sequences of the Lower Narmada River Basin**

The Narmada River, the largest river of peninsular India, flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismo-tectonic feature (Biswas, 1987). A major part of the course of the Narmada River falls within the rocky area comprising Late Cretaceous – Eocene basaltic lava flows, belonging to the Deccan Trap Formation. The river follows a constricted course in this reach, characterised by waterfalls, rapids, scablands and gorges (Rajaguru et al., 1995). The true alluvial reach of the Narmada is encountered in its lower part within the state of Gujarat. This reach is about 90 km in length and forms the southern margin of the N-S extending Gujarat Alluvial Plains. A significant feature of the lower Narmada valley is the deposition of a huge thickness of Tertiary and Quaternary sediments in a fault-controlled basin. To the south of the ENE-WSW trending Narmada–Son Fault (NSF), the Tertiary rocks and basaltic flows of Deccan Trap Formation occur on the surface, while to the north they lie in the subsurface and are overlain by Quaternary sediments. However, the overlying Quaternary sediments, having a maximum thickness of ~800 m (Maurya et al., 1995), still remain unclassified. Drill data from some of the deepest wells in the basin have revealed occurrence of Deccan Trap at depths of ~6000 m, followed by an Archaean basement (Roy, 1990). The Tertiary sediments, outcropping to the south of the NSF, represent the full sequence from Eocene to Pliocene, overlying the Deccan Trap, and show extensive deformation in the form of several ENE-WSW trending anticlinal highs and ENE-WSW and E-W trending reverse faults. Neotectonic studies along the NSF have been singularly lacking. However, some studies dealing mainly with the channel form, fluvial processes and hydrological aspects have been restricted to the middle and upper reaches of the Narmada River (Kale et al., 1994; Rajaguru et al., 1995; Gupta et al., 1999).

**Geological and tectonic setting:**
The Narmada River, the largest river of peninsular India, flows along the ENE-WSW trending Narmada-Son Fault (NSF), a well-known seismo-tectonic feature (Biswas, 1987). A major part of its course falls within the rocky area comprising Late
Cretaceous – Eocene basaltic lava flows which belong to the Deccan Trap Formation (Fig. 13). The river follows a constricted course in this reach, characterized by waterfalls, rapids, scablands and gorges (Rajaguru et al., 1995). The true alluvial reach of the Narmada is encountered in its lower part within the state of Gujarat. This reach is about 90 km long and forms the southern margin of the Gujarat Alluvial Plains. A significant feature of the lower Narmada valley is the deposition of a huge thickness of Tertiary and Quaternary sediments in a fault-controlled basin in the downthrown block to its north (Fig. 13). To the south of the ENE-WSW trending Narmada–Son Fault (NSF), the Tertiary rocks and basaltic flows of Deccan Trap Formation occur on the surface while to the north they lie in the subsurface and are overlain by Quaternary sediments. The Quaternary sediments, although having a maximum thickness of ~800 m (Maurya et al., 1995), still remain largely unclassified. Drill data from some of the deeper wells in the basin have revealed occurrence of Deccan Trap at a depth of ~6000 m, followed by an Archaean basement (Roy, 1990). The Tertiary sediments, outcropping to the south of the NSF, represent the full sequence from Eocene to Pliocene, overlying the Deccan Trap, and show extensive deformation in the form of several ENE-WSW trending anticlinal highs and ENE-WSW and E-W trending reverse faults (Fig. 13).
Geomorphology:
The lower Narmada valley can be divided into four broad geomorphic zones, spread across the four major morpho-tectonic segments. These are (1) an upland zone, dominantly on basaltic rocks but also on Cretaceous sandstones of Bagh Formation at places, (2) a lower highland on Tertiary rocks near the confluence with the sea, (3) a vast alluvial plain, which corresponds with the basin part, and (4) a narrow coastal zone dominated by mud flats (Fig. 13). Topographic profiles and field studies in the upland area reveal a rugged topography with steep escarpments bounding the mesa tops, flanked by deep and narrow gorges along the courses of several streams. Since the area consists mostly of south-dipping basaltic flows, the ridges and the associated intra-montane valleys trend in ENE-WSW direction (Joshi et al., 2013a). The lower highlands on the Tertiaries exhibit a hummocky topography in conformity with the anticlinal folds and faults. The straight ENE-WSW trending mountain-front scarps along the northern edge of the basaltic uplands and the along the lower Tertiary highland mark the NSF, beyond which lies the alluvial basin fill. The area is characterised by deep ravines, uplifted terraces, abandoned cliffs (palaeo-banks), incised cliffy banks and entrenched meanders (Chamyal et al., 2002; Joshi et al., 2013a). The alluvial plain between the ENE-WSW trending mountain-front scarps and the Narmada River has a gentle northward slope, while the plain to the north of Narmada River has a gentle slope towards WSW.

The geomorphic set up of the lower Narmada differs considerably from that in the middle and the upper reaches of the river, as described by Rajaguru et al. (1995) and Gupta et al. (1999). The river emerges from the Trappean uplands after crossing the NSF near Garudeshwar and follows a NW oriented fault-controlled course up to Tilakwada. The river then flows in a general WSW direction and exhibits large and deeply incised meanders. The Orsang, the Aswan, the Men and the Bhuki are the major rivers joining the Narmada from the north. The Karjan, which drains a major part of the trappean uplands in the lower Narmada valley, meets the Narmada from the south. The other tributary, the Madhumati River, drains the western fringe of the trappean upland. Between the Karjan and the Madhumati rivers there are several north-flowing small streams which meet the Narmada. The streams draining the lower highlands on the Tertiary rocks join the Narmada in the estuarine part, and their courses conform to the structural features in the Tertiary rocks.

The present drainage of the lower Narmada valley consists of deeply incised rivers, as evidenced by 40-50 m high alluvial cliffs and deeply entrenched meanders. Even the smallest streams, particularly those joining from the south, are found to have incised by 20-25 m. Presence of deep gullies (ravines), uplifted Holocene terraces, entrenched meanders and palaeo-banks, which comprise of abandoned, 15-30 m
high alluvial cliffs away from the present channel, suggest neotectonic activity in the area. The Narmada River exhibits characteristics of an underfit stream, characterized by narrow channels inside a wide belt of terraces (Dury, 1970). Even the largest seasonal floods do not overtop the cliffy banks (Gupta et al., 1999). Presently, the Narmada River has a tendency to shift towards the north (Agarwal, 1986). However, no traces of palaeochannels are found beyond the channel belt marked by a series of palaeo-banks. The meanders continue to grow beyond the channel belt, conforming with the northward shift of the river. Close examination of the palaeo-banks with the present channel confirms that the Narmada River has preferentially shifted towards the north. In the lower reaches the straight palaeo-bank coincides with the NSF, suggesting that the Narmada might have shifted away from the NSF due to neotectonic activity along this fault.

**Geomorphological surfaces:**
Four major geomorphic surfaces have been mapped in the lower Narmada valley (Fig. 13). These are: (1) the alluvial plain ($S_1$), (2) the extremely dissected ravine surface ($S_2$), (3) a gravelly fan surface ($S_3$), and (4) the flat-topped valley fill terrace ($S_4$). The almost flat but gently-sloping alluvial plain, which occupies a major part of the area, has been designated as the $S_1$ surface. This surface is extremely dissected in the vicinity of the river valley and exhibits gullies as deep as 20-30 m. We term this extensively gullied ravine surface as $S_2$ to distinguish it from the un-dissected alluvial plain and the fundamental importance of the extensive dissection in the geomorphic evolution of the area. The $S_3$ surface is a gravelly surface comprising a series of alluvial fans deposited along the mountain-front scarps of the NSF near Rajpipla. This fan surface is bounded by a NW-SE trending fault passing through the Narmada River on its eastern side and by a NNW-SSE trending fault passing through the Karjan River, a tributary of the Narmada, on its western side. The $S_4$ surface is a wide flat-topped terrace surface of 5-12 m height, which occupies a deeply incised stream valley. The terraces show no evidence of ravine erosion and abut against the abandoned cliffs (palaeo-bank) of $S_1$ and $S_2$ surfaces.
Lithostratigraphy and Sedimentation History

**S₁ and S₂ surfaces:**
The sediments that comprise the S₁ and S₂ surfaces are exposed along the 40-45 m high incised cliffs along the lower Narmada valley (Fig. 14). The sediment succession shows a basal clay, overlain by alluvial fan facies, and an alluvial plain facies dominated by overbank sediments (Fig. 14).

**Basal clays:**
The oldest deposit of the exposed sediment succession is a highly pedogenised mottled clay horizon, showing vertisol characters like extensive fractures giving rise to blocky aggregates, pseudo-anticlines and hydroplastic slickensides along the fracture surfaces. The deposit occurs at the base of the exposed sediment column (Fig. 14) and is readily identifiable owing to its laterally consistent occurrence and uniform lithology. Micro-faunal studies have yielded a rich assemblage of shallow marine foraminifers. The basal clays are overlain by thick fluvial sediments, which comprise two principal alluvial facies – the alluvial fan facies and the alluvial plain facies (Fig. 14).

![Figure 14](image-url)

**Fig. 14.**
Stratigraphy and lateral facies variation of Late Pleistocene sediments forming S₁ and S₂ surfaces in lower Narmada valley (after Chamyal et al., 2002).
**Fluvial sequence:**
The exposed sediments of the lower Narmada valley indicate two distinct phases of changes in the fluvial regime. One is the multi-distributary channel system that deposited the alluvial fan sediments (Chamyal et al., 1997, 2002), followed by finer alluvial plain sequence deposited by a large river in an alluvial plain setting. The reasons for the sudden change of multi-distributary river system to a more integrated single channel river system are not clear. The observed sedimentary characteristics of the alluvial plain sequence discussed above indicate a low sinuosity, single-channel large river that was hyper-avulsive. On a conservative estimate, the avulsions may have taken place on a scale of hundreds of years. The river was characterised by a ~ 8-15 m deep channel that was ~70-80 m wide, even during low discharge levels. Present-day large rivers show similar characteristics (e.g. Brahmaputra; Coleman, 1969) in which the sediments show large-scale bedforms while the river migrates at a high rate. Presently, the Narmada has a large drainage basin, much of which lies in the humid region further to the east of the Gujarat Alluvial Plain. This accounts for the high discharge levels of the Narmada River, which is next only to those of the Brahmaputra and the Ganga (Coleman, 1969).

The phase of alluviation up to the palaeosol appears to be synchronous regionally and globally. Studies in the adjacent river basins of the Mahi, the Orsang (Juyal et al., 2000; 2004) and the Sabarmati (Tandon et al., 1997) suggest a dominantly semiarid climate during large part of the Late Pleistocene and an ephemeral river system. Studies on the alluvial plain sedimentation in lower Narmada valley, however, indicates deposition by a large river which was sustained by a climate significantly wetter than at present. Although a general correlation of the depositional phases during Late Pleistocene is possible (Chamyal et al., 2002), the large-scale sedimentary bedforms of the type described here are not observed in the Mahi and the Sabarmati basins. The exposed sediments and the modern discharge levels of the Narmada River, therefore, present a contrasting picture as far as Gujarat Alluvial Plain is concerned.

The Narmada River in the Late Pleistocene has been inferred to be a mobile meandering river which carried large quantities of sand (Gupta et al., 1999), with periods of large floods (Kale et al., 2003). Studies on Holocene palaeo-flood deposits in central India (Kale, 1999; Kale et al., 1994; 2003; Ely et al., 1996) have revealed a strong correlation between periods of extreme discharges and stronger monsoons. We, therefore, infer that the alluvial plain sediments of the lower Narmada valley suggest humid climate in the large catchment area located further to the east. Additional evidence for a large catchment of the Narmada River during Late Pleistocene is provided by the dominance of sub-rounded clasts in the alluvial fan
sediments (Chamyal et al., 1997), which underlie the alluvial plain sediments. The sub-rounded clasts (a deviation from the normal angular clast composition of alluvial fans) has been attributed to longer distance of transport before they were deposited in an alluvial fan environment in the lower Narmada valley. This suggests that the Narmada River has maintained a large catchment at least during the last 100 ka. The alluvial plain sequence of the lower Narmada valley also suggests discharges higher than the present-day Narmada River in the upper part of the Late Pleistocene. The palaeosol near the top of the sequence, however, correlates with the regional phase of intense pedogenic activity in the Gujarat Alluvial Plain before the Last Glacial Maximum. The overlying stratified sands and silts reflect a significant weakening of fluvial regime during the arid phase of the Last Glacial Maximum, though the river still remained perennial, again mainly because of the large catchment area of the drainage basin.

Overall, the 50-25 ka period in north India is considered to be a period of widespread fluvial aggradation, as found from the studies on alluvial sequences in Gujarat Alluvial Plain (Tandon et al., 1997; Juyal et al., 2000; Maurya et al., 2000), Maharashtra upland rivers (Kale and Rajaguru, 1987), Central Narmada (Badam et al., 1986; Gupta et al., 1999; Kale et al., 2003), Son and Belan valleys (Williams and Clarke, 1984) and the Indo-Gangetic plain (Singh, 1996). Well dated global fluvial sediment records from Guadalope basin in Spain (Fuller et al., 1998), the entire Mediterranean region (Macklin et al., 2002), Thames River (Maddy et al., 2001), Mississippi River (Autin, 1996; Blum et al., 2000), and Australia (Nanson et al., 1992; Kershaw and Nanson, 1993) also suggest enhanced fluvial aggradation under a humid climate during the 50-30 ka period. There is thus a strong reason to believe that the deposition of alluvial plain sediments with large-scale bedforms below the palaeosol in the lower Narmada valley, was by a large river that operated in a more humid condition than at present, and possibly in response to global climatic perturbations. The humid climate, together with a large catchment area, contributed to high discharge, leading to the formation of large-scale sedimentary structures in these sediments.
Geomorphic Evolution

Late Pleistocene:
The sediments forming the $S_1$ and $S_2$ surface date back to Late Pleistocene. The sedimentation commenced with the deposition of the marine basal clays during the last interglacial high sea at $\sim 125 \text{ ka}$ which is presumed to be about $+7 \text{ m}$ as revealed by the studies on the adjacent Mahi river basin (Rachna Raj et al., 1998) and Saurashtra coast (Pant and Juyal, 1993). Regression of this sea led to the initiation of fluvial sedimentation. The fluvial sediments indicate deposition in two fluvial macroenvironments— the alluvial fan environment and the alluvial plain environment. The alluvial fan deposits overlie the marine clays followed by the alluvial plain sediments.

Optimal conditions for fan development are created in regions undergoing extension (Blair and Bilodeau, 1988), like in the Basin and Range province of western North America, the Middle Eastern Dead Sea rift in the Middle East, and the East African rift system. Extensional basin settings are especially conducive for long-term fan development, leading to deposition of fan sequences hundreds of metres thick, but in a compressive tectonic regime the long-term development of fans is hindered due to the stronger component of lateral tectonic deformation (Blair and McPherson, 1994). The transformation of the Narmada-Son Fault (NSF) from a normal fault during the Tertiary to a reverse fault during the Quaternary is implicit in the seismic studies of the area (Roy, 1990). Additional evidence for prevalence of compressive stress regime in the lower Narmada basin is provided by numerous reverse faults in the Neogene sediments exposed immediately to the south of the Narmada-Son Fault (Agarwal, 1986). These evidences suggest that both the fans, Fan 1 and Fan 2, were formed in a compressive tectonic environment. This could be a reason why the maximum thickness of the fan sequences is about 70-80 m only, of which about 35 m is exposed. The compressive stress regime affected the fan morphology due to which both fans show a rather elongated shape, resulting in alluvial fans of unusual axial lengths (Chamyal et al., 1997). The alluvial fan sediments are overlain by a thick sequence of alluvial plain facies, which indicate termination of fan sedimentation and establishment of a more integrated drainage system.

Several studies document the effects of syn-sedimentary subsidence on the alluvial plain sedimentation (Shuster and Steidtmann, 1987; Brown and Plint, 1994; Kraus and Middleton, 1987; Kraus, 1992; Jordan, 1981; Hagen et al., 1985). Absence of soil profiles in the thick over-bank fines of the study area is indicative of syn-sedimentary subsidence of the basin. Soils can only develop on land surfaces which are relatively stable (Bull, 1991; Marriot and Wright, 1993). Since the facies associations contain no pervasive fining upward trends or lateral accretion features we assume that there
have been no major deviations in the mean flow directions. It is unlikely that a high-sinuosity channel will produce stacked system of fluvial deposits showing these characteristics (Shuster and Steidtmann, 1987). Strong similarity in the orientation of the deformation structures suggests subsidence in a thrusting environment along the NSF, which is consistent with the subsurface studies. A study by Shuster and Steidtmann (1987) in an area having almost similar structural setting as in the present study area, suggests that if and when subsidence rate is low, sand bodies with high degree of persistence and inter-connectivity can be expected, while if and when rapid subsidence takes place, such persistent sand bodies may not occur. We, therefore, infer that the deposition of these sediments took place when a low-sinuosity and relatively fixed river system existed in a slowly subsiding basin.

Syn-sedimentary subsidence of the basin due to differential movement along the NSF is indicated by the alluvial fan sediments, thick over-bank sediments and the deformation structures. Folding and faults with reverse movement in the over-bank sediments suggest a compressive stress regime along the NSF. This was followed by a brief period of tectonic stability, as suggested by the 4-5 m thick palaeosol (red soil) that can be correlated with the red soils exposed in the Mahi and Sabarmati River basins. A blanket of aeolian sediments over the fluvial sediments suggests a phase of widespread aridity that corresponded with the expansion of Thar Desert into the Gujarat Alluvial Plains (Allchin et al., 1978).

**Early Holocene:**
Formation of extensive ravines and 45-50 m cliffs along the incised streams suggest that the ravine formation post-dated the aeolian sedimentation of Late Pleistocene period. Absence of ravines on the S, surface consisting of mid-Late Holocene sediments, helps us to constrain the age of the ravine formation phase (and that of the cliff formation and stream incision) to the Early Holocene (~10 to 6 ka), which was a period of rapid sea level rise (Chappell and Shackleton, 1986; Hashimi et al., 1995). This means that the ravine formation and the stream incision were not related to the lowering of the sea level during the LGM. Had such fluvial activities taken place during the low sea level of LGM, one would have expected a much randomised distribution of aeolian sediments, preferentially within the gullies, but this was not so even in the Mahi and the Sabarmati basins where a more complete aeolian record has been found (Tandon et al., 1997; Juyal et al., 2000; Maurya et al., 2000). The aeolian sediments occur as a capping over the underlying fluvial sediments and are clearly along the incised cliff sections and in the ravines.

The above evidences suggest tectonic upliftment of the lower Narmada valley along the NSF during Early Holocene period. It resulted in the formation of extensive
ravines (S₂ surface) and a deeply incised stream valley. The strongest supporting evidence for the Early Holocene tectonic uplift of the area comes from the sea level curves of the west coast of India which suggests a tectonic component of about 40 m at this time (Rao et al., 1996). Assumptions of increased precipitation during the Early Holocene humid phase can be discounted for following reasons: (1) the severe erosional phase occurred during a period of rapid sea level rise; (2) the sea level curves of the west coast of India indicate a strong tectonic component of about 40 m during Early Holocene; (3) the geomorphic evidences like consistent presence of >40 m high cliffs of Late Pleistocene sediments, deep gullies, entrenched meanders and anomalous NNW tilting of the S₁ surface between Narmada River and the NSF; and (4) high precipitation of Early Holocene did not produce similar effects in more humid region like the Indo-Gangetic plain, a foreland basin to the south of the Himalayas. Even today, the Indo-Gangetic plain receives roughly three times more rainfall than the lower Narmada valley. The major rivers, the Ganga and the Yamuna having very high discharge in Indian subcontinent, should have produced identical geomorphic features of incised river valleys and extensive ravine erosion. Instead, these rivers exhibit extensive floodplains, large natural levees and back-swamps (Singh, 1996). That leaves tectonic uplift as the main cause for dissected S₂ surface in lower Narmada basin. However, discharge level was perhaps much higher than at present, as indicated by the palaeo-banks consisting of Late Pleistocene sediments (S₁ and S₂ surfaces). The features suggest a much wider and less sinuous channel belt for the Narmada River during the period. Even the largest seasonal floods are not enough to fill the entire present-day valley (Gupta et al., 1999).

As a preliminary conservative estimate, not considering the likely cliffy section below the exposed base, an uplift of about 40 m can be inferred from the 40-45 m high incised cliffs. This means that the 35-40 m high precipitous cliffs along the river actually led to an underestimation of the total amount of incision prior to the Mid-Late Holocene aggradation. The tectonic uplift during Early Holocene perhaps suggests inversion of an earlier subsiding basin. Such inversions of the basin have been common during the Tertiary period, and are well recorded in the sediments of this age (Roy, 1990).

The displaced Late Pleistocene sediments across NSF in the Narmada and the Karjan river valleys, the NNW tilting of the S₁ surface consisting of Late Pleistocene sequence, anomalous topographic slope in the same direction, and incised cliffs up to 20-30 m in the streams that flow along this slope in the area between NSF and the Narmada River, indicate a differential uplift along the NSF during Early Holocene. The displacement of sediments of the S₁ surface across the NSF indicates differential movement of about 35 m along the NSF during Early Holocene. The block between
the Narmada and the Karjan rivers, bounded by the NSF and the two other cross-faults, suffered subsidence leading to the formation of a series of alluvial fans over the Late Pleistocene sediments. The 5-8 m incised cliffs of the streams also suggest that this block escaped the uplift-induced large scale incision and ravine erosion that were going on simultaneously in other areas of the lower Narmada valley.

**Middle Holocene to Recent:**

The Mid-Late Holocene valley complex is the product of a Holocene high-sea-level-induced deposition in a deeply incised fluvial valley. The Mid-Late transgression was within the incised fluvial valley, which resulted in estuarine sedimentation in the lower reaches and fluvial deposition in the upper reaches. A significant slowing down of the tectonic uplift facilitated the encroachment of the sea into the valley and creation of a depositional wedge, which extended up to the foothills. The 5-10 m exposed thickness of the valley fill sediments reveal tide-dominated estuarine deposition in the lower reaches and fluvial deposition upstream of the tidal reach. Seismically-induced soft sediment deformation features from comparable terrace sediments in the Mahi valley (Maurya et al., 1998) and the Orsang valley (Maurya et al., 2000) suggest tectonic instability of the region during the period of valley fill sedimentation. Comparison of the present estuary with the one indicated by the palaeo-banks against which the terraces abut, reveals that the present mouth of the Narmada River has roughly retained the original funnel shape of the estuary formed during the Mid-Late Holocene. However, the size of the estuary is now considerably reduced. The present estuarine reach contains several islands, which are coeval with the terrace surface and are well above the present tidal range. Hence, they are the products of estuarine processes of the Mid-Late Holocene and not those of the present day. Funnel-shaped morphology and increasing tidal energy landward are characteristics of tide-dominated estuaries (Wright et al., 1973).

Existing data suggest that the Mid-Late Holocene sea level has remained almost at the same level up to the present with minor fluctuations (Chappell and Shackleton, 1986; Hashimi et al., 1995). The Mid-Late Holocene sediments show tilting of $10^\circ$-$20^\circ$, which is more pronounced in the vicinity of the NSF, suggesting that the incision and upliftment of the valley fill terraces well above the present day tidal limits is related to the continued differential uplift along the NSF. Evidence of tectonic uplift from the coast is also reported in the form of raised mudflats at 2-4 m above the present sea level (Merh, 1993). Currently, the river occupies the northern margin of the Early Holocene channel belt and is clearly more sinuous. It exhibits a narrow channel with wide meanders in between a set of Mid-Late Holocene terraces ($S_4$ surface), a typical pattern of under-fit streams (Dury, 1970).
Neotectonic studies are mainly based on geomorphic data associated with active faults, as well as on deformation structures. The geomorphic evidences observed in the lower Narmada valley are the young mountain-front scarps delimiting the basaltic uplands and marking the Narmada-Son Fault, youthful channel morphology of the Narmada River and other rivers, as testified by consistent presence of incised vertical cliffs, entrenched meanders, extensive and deep ravines, uplifted Holocene terraces, anomalous slope variation of $S_1$ surface, especially to the south of the Narmada River, and remarkable correlation of the drainage with structural features in the lower uplands on the Tertiary. Two major phases of tectonic activity along the NSF are recorded. The first phase includes the Late Pleistocene when slow syn-sedimentary subsidence of the basin took place along the NSF, which allowed for uninterrupted sedimentation except for brief periods of pedogenesis of basal clays and the over-bank sediments. Syn-sedimentary subsidence of the basin in compressive tectonic setting is evidenced by the hindered alluvial fan sedimentation, thick over-bank sediments and associated sediment deformation. The second phase includes the Holocene, which is marked by basin inversion due to differential uplift along the NSF. Inversion of basin after a prolonged period of subsidence is common (Ziegler, 1983). The period of inversion is usually a period of net erosion (Mather, 1993). As stated above, two phases of uplift during Holocene could be recognised. The first of these occurred during Early Holocene which formed extensive ravines and a deeply incised fluvial valley. The second during Late Holocene to Recent uplifted the Mid-Late Holocene sediments forming terraces.

The Early Holocene tectonic activity recorded in the lower Narmada valley, possibly, has wider ramifications when viewed in the larger perspective of Indian plate. Available models of neotectonic deformation of the Indian plate indicate that the peninsular India has been undergoing high compressive stresses due to the sea floor spreading in the Indian Ocean and locking up of the Indian plate with the Eurasian plate in the north (Subramanya, 1996). Much of these N-S directed stresses have been accommodated by the under-thrusting of the Indian plate below the Eurasian plate. A part of these compressive stresses are accumulated along the NSF, a major E-W trending crustal discontinuity in the central part of the Indian plate. Tectonic activity of significant magnitude during the Early Holocene has been reported from the sea level studies of the west coast and from the Himalayas, located at the trailing and leading edges of the Indian plate, respectively. In the Himalayas, the termination of lacustrine sedimentation has been attributed to tectonic activity during the Early Holocene (Kotlia et al., 2000). Together, the evidences suggest a renewed phase of extreme compression of the Indian plate, which led to tectonic inversion along the NSF in the lower Narmada valley. Significant increase in compressive stresses accumulating on an intra-crustal fault like the NSF can transform a previously
subsiding basin into an uplifting one. Since the NSF has been characterised by compressive stress regime throughout the Quaternary, we believe that such variations in the degree of compression, which can in turn be interpreted in terms of varying rates of plate movement, alone are responsible for the Late Pleistocene subsidence and Holocene tectonic inversion in the lower Narmada valley. Studies from other parts of the NSF are needed to confirm the continuity of these movements along the length of the fault.

As stated earlier, the present landscape of the lower Narmada valley comprises of four geomorphic surfaces, which have evolved mainly due to tectonic activities along the NSF in a compressive stress regime. The sediments comprising the S₁ and the S₂ surfaces were deposited in a slowly subsiding basin during the Late Pleistocene. The Holocene period is marked by the inversion, which had earlier suffered subsidence. The inversion of the basin is due to significant increase in the compressive stresses along the NSF during Early Holocene, resulting in differential uplift of the lower Narmada valley. The continuation of the compressive stress regime due to the ongoing northward movement of the Indian plate indicates that the NSF is a major candidate for future intra-plate seismicity in the region.

The alluvial plain sequence of the lower Narmada valley is characterised by the dominance of over-bank sediments and large-scale sandy bedforms. The sequence was deposited by a low-sinuosity large river with discharge higher than during the present. The river migrated laterally across the alluvial plain at a high rate. The deposition was mainly controlled by the humid conditions prevailing in the large upstream catchment area further to the east of the present study area, and not by the semi-arid climate of the Gujarat Alluvial Plain. Studies so far suggest that the Narmada River has retained a large catchment since the last 100 ka.
Stop 1: Gamod Section

Along the banks of the river Aswan the 15 m thick succession of Gms facies is characterized by convex upward surfaces. A major bounding surface separates two vertically stacked packages, each containing four cycles of the Gms facies (Chamyal et al., 1997). At the base of the succession is a sand sheet deposit (Sm facies), which separates the underlying sheet of the Gms facies from the eight cycles of debris flows. The dominant clast size is 10 cm. Deviation from this size occurs in the form of ~16 cm tabular blocky clasts. No St and Gp facies are observed at this locality.

Stop 2: Tilakwada Section

The sediments of Alluvial Fan-1 are best exposed at Tilakwada, where the fan deposit occurs all along the cliffy banks of the Narmada (Fig. 15, 16). The section illustrates various characteristics of facies development, both spatially and temporally (Chamyal et al., 1997).

The sedimentary facies at Tilakwada section typically point to deposition in an alluvial fan environment (Table 1). The 30 m thick bank scarps expose a succession of a ubiquitous packet of Gms facies. The facies is present at the base of all exposures in the area. These gravels have lobate geometries, contained within which are lenses of the Gp facies. The clasts have thin white veneers of calcite, which has also cemented the gravel. The clasts are basaltic and some show remnants of pre-depositional spheroidal weathering. Nesting of clasts is present. The Gp1 facies occurs intercalated between Gms gravels, and progressively...
becomes more prominent towards the top of the section. The alluvial architecture, when traced over long exposures using panoramic photographs, reveals the major contribution of the Gms facies. The oldest exposed sediments at Tilakwada are made up of 2 m thick, matrix-supported gravels. At places the thickness is about 6.5 m. The clasts range in size from 25 to 35 cm, and are dominantly basaltic. These are bounded together by a sand matrix. The top of the sediment succession is represented by a massive sand of about 2.5 m thickness, showing no internal stratification. This internally unstratified horizon was dated by Blue Green Stimulated Luminescence (BGSL) technique at PRL, Ahmedabad, and is found to be <90 ka in age (Chamyal et al., 2002). Over the massive sand deposit lies a planar, cross-stratified gravel bed having a thickness of about 5 m. At places it alternates with the massive sand horizon.

The alluvial architecture was constructed by both the confined and the unconfined flows. Of the primary depositional processes that directly contributed to aggradation of the fan, viscous debris-flows played a major role, with a minor contribution by sheet-floods. Debris-flow deposits (Gms facies) make up over 70% of the alluvial architecture. Debris-flows aggraded the fan at both proximal and distal ends. The maximum clast size decreases progressively down-fan, in agreement with the expected fall in flood velocity. Evidence of intervening quiescent periods between the fan aggradation events is present in the form of large-scale planar cross-stratified gravel (Gpt) and trough cross-stratified sand (St) facies. Braided rivers with longitudinal gravel bars dominated the surface of the fan during these phases. A major deviation from the norm is observed in the clast roundness of the debris-flow deposits. Most of alluvial-fan deposits are recognized by their angular to sub-angular nature. Angularity of clasts has been stressed and the only exception accommodated is a conglomeratic provenance. In the present case it is suggested that the greatly elongated catchment area upstream of Nawagam (fan apex) was a determinant. Rounding of clasts took place when the angular fragments were transported as bed load along the length of the Narmada. The flat base suggests that these clasts rested on a stream bed while the exposed surface of the clast was modified to its present shape by the stream flow. These sub-rounded clasts were then eroded from the bars, remobilized and entrained in viscous debris-flows during flash floods.
Table 1. Summary of major sedimentary facies comprising the alluvial fan sediment succession at Tilakwada. Facies coding scheme is after Miall (1985).

<table>
<thead>
<tr>
<th>Facies Code</th>
<th>Description</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gms</td>
<td>Inversely graded cobbly to boulder gravels, having cross-sectional lobate geometry. Maximum clast size is up to 150 cm. Large clasts within each unit appear to ‘float’. Clasts are usually sub-rounded basalts.</td>
<td>Debris flow deposits</td>
</tr>
<tr>
<td>Gms</td>
<td>Gravel-sand couplets, stratified, but no internal stratification. Sandy units contain pebbles but cobbles are absent. Clasts are usually sub-rounded basalts.</td>
<td>Sheet flow deposits</td>
</tr>
<tr>
<td>Sm</td>
<td>Sand sheets, massive with lobate flow deposits cross-sectional geometry, no visible internal stratification.39.1</td>
<td>Sheet flow deposits</td>
</tr>
<tr>
<td>GPI</td>
<td>Planar cross-stratified gravel; may occur as solitary set or co-set; show normal grading with clasts of sub-rounded basalt. At times cobbly basalt lag deposits are present.</td>
<td>Longitudinal gravel bars</td>
</tr>
<tr>
<td>Gp2</td>
<td>Planar cross-stratified gravel with lensoid geometry. Normally graded; intimately associated with Gms facies</td>
<td>Re-channelized flows genetically related to debris flow events</td>
</tr>
<tr>
<td>St</td>
<td>Trough cross-stratified sand.</td>
<td>Channel-fill element</td>
</tr>
</tbody>
</table>
Stop 3: Chandod Section

The 35 m thick fluvial sediment succession exposed at Chandod (Fig. 17, 18) has been considered as the basis for the reconstruction of physical stratigraphy of the alluvial plain sediments above the alluvial fan sequence (Bhandari et al., 2005). The base of the section is characterized by a 3 m thick planar cross-stratified gravel (size ranging from 10-15 cm) and the matrix holding the gravels is sandy. These are overlain by 2 m thick planar cross-stratified sand, which is overlain by planar cross-stratified gravels having a thickness of 4 m.

Fig. 17.
Photomosaic of an extensive cliff at Chandod.
All units show erosional bases (after Bhandari et al. 2005).
1) distal alluvial fan facies, 2) large channel fill sands,
3) giant epsilon cross bedded strata, 4) horizontally stratified overbank strata,
5) palaeosol, 6) thinly stratified sands and silts.

Fig. 18.
Sketch showing vertical relationship between sediments exposed along the > 400 m long cliff at Chandod, as shown in Fig. 17 (Bhandari et al. 2005).
Above the planar cross-stratified gravels a 10-m thick horizontally stratified sand is deposited. This sand horizon is studded with rhizo-concretions and horizontally-stratified bedded calcretes. These are overlain by a 5-m thick sand showing no internal stratification, which is again overlain by pedogenized sand of about 5 m thickness. A soil has developed over the fluvial over-bank fine sand and silt, and shows typical fracturing in the form of blocky aggregates. There is copious amount of calcrete throughout the horizon. The soil shows typical reddish brown colour. Overlying this is 6 m thick deposit of massive sand which shows no internal stratification.

At two stratigraphic levels channel fills are observed, which are separated by the epsilon cross-stratified facies (Fig. 17, 18). The older channel fill overlies gravel deposits of the alluvial fan facies with a deeply scoured base, and shows a gentle concave geometry, filled by vertically-accreted fine to medium sand. Overall, the structure indicates a westward-oriented channel that was ~70 m wide and ~4 m deep. Each sheet of channel fill is about 1 m thick and the channel axis decreases at the margins to 0.3 m. The sand shows fine horizontal laminations and a complete absence of lateral accretion feature. This suggests filling up of the channel primarily through vertical accretion in an almost standing body of water. It normally happens in chute cut-offs where deposition takes place in the remaining body of standing water after the channel is abandoned. The channel margins show a low dip of 15-20°, which means that the channel was not produced by incision. The younger channel fill is exposed at the southern extremity of the ~ 400 m long outcrop. Its shape suggests a much deeper and larger channel although only about 30% of the total structure is observed, the rest having been eroded away by the present river. The channel fill occurs above the epsilon cross-bedded strata. Its margin has a steep dip of about 30°. Extrapolation of the channel margin suggests a ~80-90 m wide and ~10 m deep channel. The channel trough is filled by sand sheets with concave-up geometry with internal stratification. Laterally sediments of this channel fill are found to grade into stratified over-bank sand. The epsilon cross-strata at Chandod range in thickness from 10 m to 15 m, and terminate against the overlying thick-bedded over-bank facies. Laterally, the epsilon bed passes into horizontal strata, and further away merges with the over-bank deposits. Its deposition can be attributed to lateral migration of a 15-20 m deep sand-bed stream. Similar large-scale epsilon cross bedded strata has been attributed by Jackson (1978) to deposition in deep water.
Stop 4: Phulwadi Section

This section on the right bank of Shamariyakhadi River exposes alluvial fan sediments forming the S4 surface in front of the NSF scarps (Fig. 19, 20). The alluvial fan is one of the five small coalesced alluvial fans recognized along the NSF scarps to the east of Rajpipla. The fans form a distinct northward sloping alluvial surface. The exposed sediments along the river cliff represent sediments of the medial part of the fan. The sediments are made up of matrix-supported gravels, horizontally-stratified gravels, planar cross-stratified gravels and sand (Fig. 20).

The gravels are sub-angular to sub-rounded, and are poorly sorted. Four aggradational phases of Gms facies are recognized. Sp and Sh facies occur as lenses or as continuous bands. The Sp, Sh and Sm facies represent the quiescent periods between the fan aggradation events. Overall, the section shows domination of Gms facies, and indicates cyclic aggradation phases. This suggests deposition mainly by debris flows and sheet flows.

Fig. 19.
Upstream view of the incised cliff at Phulwadi showing early Holocene fan deposits with distinct layers of matrix-supported gravels and horizontally-stratified sand.

Fig. 20.
(A) Four aggradation phases of Gms facies with intervening Sh facies at Phulwadi.
(B) Lensoid nature of Sp facies overlain by Gp facies and underlain by Gh facies.
Day 4: 15/11/2017
Vadodara to Juna Ghanta and Nava Ghanta along the Nandikhadi River, Khojalwasa, Tejpur, Karjan Dam, and back
Stay at Vadodara.

The lower Narmada basin exposes some good examples of tectonic landforms and structural features along the Narmada – Son Fault, which are proposed to be visited during the day. Before describing the sites we provide a brief account of the tectonic geomorphology of the fault zone.

Tectonic Geomorphology of the Narmada-Son Fault Zone

The Narmada–Son Fault:
The Narmada–Son Fault (NSF) trends in ENE-WSW direction and is laterally traceable for more than 1000 kms. It divides the Indian plate into two geologically distinct provinces: the Vindhyan-Bundelkhand province to the north and the Deccan province to the south, and has a long tectonic history dating back to the Archaean times (Ravi Shankar, 1991). According to Ravi Shankar (1991) NSF is part of a large, composite, tectonically-controlled zone through the middle of the Indian plate, which can be termed as ‘SONATA’ zone (abbreviated form of the Son-Narmada-Tapti Lineament zone). The Narmada and Tapti Rivers follow these tectonic trends all throughout their course. Other synonyms used to describe this zone include the Narmada-Son Lineament (NSL; Choubey, 1971), Central Indian Shear (CIS; Jain et al., 1995) and Central Indian Tectonic Zone (CITZ; Radhakrishna and Ramakrishnan, 1988; Acharyya and Roy, 2000). Geophysical studies in the central part of this zone reveal this to be a zone of intense deep-seated faulting (Reddy et al., 1995). The zone witnessed large-scale tectono-thermal events associated with huge granitic intrusions around 2.5-2.2 Ga and 1.5-0.9 Ga (Acharyya and Roy, 2000). It was again reactivated during the Deccan volcanic eruptions during Late Cretaceous-Palaeocene periods (Agarwal et al., 1995). Profuse occurrence of E-W trending dykes suggests that the zone formed the main centre of eruptive activity (Bhattacharji et al., 1996). The entire zone is presently characterized by high gravity anomalies, high temperature gradient, heat flow and anomalous geothermal regime (Ravi Shankar, 1991), which suggest that the zone is thermo-mechanically and seismically vulnerable in the framework of contemporary tectonism (Bhattacharji et al., 1996).

Data on the NSF in this part is mainly the result of extensive geophysical surveys for exploration of petroleum reserve. The westward extension of the NSF zone into the lower Narmada valley exhibits itself as a less complex structural setting, and expressed as a single deep-seated fault (NSF) that has been confirmed by the Deep Seismic Sounding studies (Kaila et al., 1981). Seismic reflection studies have established that the NSF is a normal fault in the subsurface and becomes markedly
reverse near the surface (Roy, 1990). Reactivation of the fault during the Late Cretaceous led to the formation of a depositional basin in which marine Bagh beds were deposited (Biswas, 1987). The NSF remained tectonically active since then, with continuous subsidence of the northern block, designated as the Broach block, which accommodated 6-7 km thick Cenozoic sediments (Biswas, 1987). The total displacement along the NSF exceeds one kilometre within the Cenozoic section (Roy, 1990). However, the movements along this fault have not been unidirectional throughout. The general tendency of the basin to subside has been punctuated by phases of structural and tectonic inversion (Roy, 1990). The N-S directed compressive stresses during the Early Quaternary folded the Tertiary sediments into a broad syncline, the Broach syncline, in the rapidly subsiding northern block (Roy, 1990). The Broach syncline extends from the NSF to the Mahi River in the north. The E-W trending axis of this syncline lies to the north of the Narmada River. Corresponding anticlinal structures are found in the Tertiary rocks exposed in the southern upthrown block. Historical and instrumental records indicate that the compressive stresses still continue to accumulate along the NSF due to continued northward movement of the Indian plate. This is evidenced by the fault solution studies of the earthquakes at Broach (23rd March, 1970) and Jabalpur (22nd May, 1997), which suggest a thrusting movement (Gupta et al., 1972; 1997; Chandra, 1977; Acharyya et al., 1998).

**Stop 1: Traverse along the Nandikhadi River through Juna Ghanta and Nava Ghanta**

The Nandikhadi River is a tributary of the Narmada River, and originates in the south from the Trappean uplands. It is the most important drainage basin to the south of the Narmada River as it shows significant evidence of active tectonics (Fig. 21). In the upland zone, the Nandikhadi River is characterized by frequent occurrence of knick points, tight meanders and deeply incised channel segments (Fig. 21). The height of the knick points ranges from 1 m to 16 m. The total fall of gradient related to knick points is of ~37 m within a short distance of 1.5 km.

A coalesced group of alluvial fans, the ‘bajada’, is identified in this segment between the Karjan River and the Madhumati River (Joshi et al., 2013b). The sediments are well-exposed along the Nandikhadi River and shows a higher topographic elevation compared to those in the adjacent alluvial plains to the east of Karjan valley, to the west of Madhumati valley and the Narmada valley to the north. The altitude of the fan surface near the mountain front is 120 m above msl and it extends for ~24 km along the mountain front.
As the river course approaches the unconsolidated Quaternary sediments, it shows incision of up to 40 m, which decreases to 6-7 m in a very short distance of less than 3 km. The bajada sediments can be inspected along the cliffs exposed along the incised river. In longitudinal section, the deposits appear to be wedge-shaped (Fig. 22). The bajada surface displays plano-concave–upward geometry, created by the distally decreasing slope. The sediments can be grouped under seven distinct sedimentary facies. In approximate order of abundance, the facies identified are: matrix-supported gravel (Gmm), clast-supported gravel (Gcm), massive silty sand (Sm), soil (P), trough cross-bedded gravel (Gt), horizontally-stratified gravel (Gh), and massive brick-red sand (Ss) lithofacies. The OSL age of 25.1+1.8 ka BP obtained from the middle part of the bajada succession suggests that the sedimentation occurred during the later part of late Pleistocene. This correlates with the slow syn-sedimentary subsidence of the basin during the late Pleistocene, as documented by Chamyal et al. (2002). Compared to this, the late Pleistocene sediments exposed along the incised cliffs of Narmada River are finer as they were deposited in an alluvial plain environment (Bhandari et al., 2005). The bajada sediments are sedimentologically different but stratigraphically comparable with the sediments.
exposed along the Narmada River. It is presumed that in the downstream, the bajada sediments may show inter-tonguing relationship with the finer alluvial plain sediments of the Narmada River.

The Quaternary sediments occur at an altitude of ~120 m above msl and represent the sediments of proximal fan deposits. The succession starts with deposition of clast-supported massive gravels (Gc) that directly overlie the Deccan Trap with an abrupt contact. It consists of sub-angular to sub-rounded clasts of Deccan basalt and range in size from pebble to boulder. There is a general absence of grading despite the massive thickness, which suggests that the clast-supported gravels were deposited by low strength, pseudo-plastic debris flows. The clast-supported gravels are overlain by massive silty sand (Sm) and horizontally-stratified gravel deposits (Gh). The downstream sediment succession represents distal part of the fan comprising of soil, horizontally stratified gravels and massive silty sand (Fig. 22).

Fig. 22.
(A) Topographic cross profile of the bajada surface drawn from DEM. Note the wedge shaped coarse gravelly bajada sediments in front of the hill and their mean slope. Other surfaces down the slope are also shown (after Joshi et al., 2013b). (B) and (C) are field view of the cliff exposing bajada sediments.
Stop 2: Khojalwasa Section
The bajada sediment succession at this site represents distal part of the fan, comprised of soil, clast-supported gravels, horizontally-stratified gravels and massive silty sand (Joshi et al., 2013a). A brownish to reddish soil corresponds to lithofacies P of Miall (1996). Parent material of the soil is a mixture of clay, silt and fine sand. Hence it can be inferred that it was possibly deposited by the stream as over-bank deposits. The presence of soil suggests a sub-humid climate or a relatively wetter climate than at present. The clast-supported massive gravels correspond to the Gcm facies of Miall (1996). It consists of sub-angular to sub-rounded clasts of basalt and range in size from pebble to boulder. The massive silty sand facies (Sm) is characterized by 0.25 to 4.5 m thick horizons of fine to medium sand and silt. The sand is poorly sorted and do not show any grading. It is rich in calcium carbonate nodules and calcite sheets. The absence of sedimentary structures, massive texture and poorly sorted framework suggest that the lithofacies was deposited as sheet flood deposits by gravity flows. The horizontally stratified gravel (Gh) is the most abundant facies, deposited particularly in the proximal and medial sectors of the fan surface. The thickness of the facies varies from 5 m to 17 m. It has a clast framework and abundant coarse sandy matrix. However, the percentage of matrix varies considerably. The Gh facies represents the longitudinal bar deposits of braided channels.

Stop 3: Tejpur in Madhumati River basin
The Madhumati River is one of the major tributaries of the Narmada River, joining from the south. The river rises from the Trappean upland, drains the western fringe of the Trappean upland, and traverses through the NSF and alluvial plain to join the Narmada after a travel length of about 41 Km. The drainage characteristics within the Trappean uplands and in the alluvial zone are quite different. While in the upper reaches of the river through the Trappean zone the drainage pattern is trellis, in the lower reaches through the alluvium the pattern is dendritic. Stream density in the upper reaches is high, where the tributaries are straight, whereas in the lower reaches the stream density is low, and tight entrenched meanders can be observed. The drainage basin is elongated in NE-SW direction. The course of the Madhumati River shows a strong structural control. From Umarkharda to Dholi the river flows westward along an almost E-W trending course. At Dholi, the river takes a right angle turn to flow northward along a remarkably straight N-S oriented course up to Tejpur which lies to the north of the NSF. The straight nature of the river course and the right turn strongly suggests the existence of a N-S trending transverse fault (Fig. 23). The geomorphic evidence of the NNW–SSE trending Madhumati Fault is observed near Tejpur. The fault is represented by the displaced scarps of the NSF, which indicates a dominantly strike slip movement along this transverse fault (Fig. 23). The displaced basaltic ridge near Tejpur is locally known as the ‘Khaseli Dungar’, which literally
means a ‘shifted hill’ (Fig. 23). This fault shows a right lateral offset of the NSF for about 1 km. The presence of the fault is evidenced by the straight channel of the Madhumati River and the formation of a large, deeply-incised and compressed meander in alluvium as it emerges from the uplands. The slickensides exposed along the fault plane in basaltic rocks, on the left bank of the river, suggest oblique slip movement (Fig. 23). The incision of the river is of the order of 40 m.

The large entrenched meander near Tejpur has exposed a 35 m cliff (Fig. 23). Downstream of Tejpur, the river flows towards NW with several entrenched meanders in the alluvial zone (Fig. 23). At Rajpardi, the river takes a north-westerly turn because of the influence of the Rajpardi fault.

In the alluvial zone of Madhumati river, the late Quaternary fluvial deposits are characterized by a regular and cyclic sequence of sand and gravel. The clasts of the gravel bed consist of basalt derived from the upland. The clasts are poorly sorted and the matrix is mainly coarse to medium sand. In the lower reaches these cyclic sequences of sand and gravel overlie the clay horizon. The best and highest exposed section in the alluvial zone of the Madhumati River basin is located at Tejpur. Here the Quaternary sediments abruptly abut against the Trappean rocks along the NSF.

Fig. 23.

Fig. 23. Google Earth image of NSF zone and its structural elements near Madhumati River. Note the straight course of Madhumati River along the NNW-SSE trending transverse fault and the compressed meander near Tejpur.
The average thickness of the section on the right bank is about 35 m. The oldest exposed sediment is gravel, its thickness being about 1 m. This bed is succeeded by 5 m thick pedogenised sand which in turn is overlain by 2 m thick gravel, showing no stratification. This bed is succeeded by 5 m massive sand, which in turn is overlain by 7 m horizontally-stratified gravel, embedded with cobbles. Within this layer sand lenses of about 1 m thickness are present. This bed is overlain by 3 m thick, weakly pedogenised sandy silt, which in turn is overlain by 3 m weakly stratified gravel. This bed is overlain by a 3 m thick massive sand over which a 4 m gravel bed rests. The whole sequence is capped by 1 m topsoil.

A most interesting feature in the Tajpur section is the occurrence of a volcanic ash layer within the Quaternary alluvial succession (Fig. 24). This ash bed is correlated with the Youngest Toba tuff (Raj, 2008). The ash is unconsolidated, well-sorted, homogenous and friable to the extent of getting to fine powdery material. Glass shards make up 90% of the ash although pumice fragments are also present. Accessory minerals include quartz, felspars, biotite and occasional zircon. The details of the micro-structures of glass shard and pumice shard have been brought out very clearly by the SEM studies. The shape of glass shards ranges from blocky, cusptate, flat or platy, triangular, tri-radiate or multi-junctional (Fig. 25). Most of them show a typical bubble wall structure, which is indicative of a magmatic type of eruption.

Fig. 24.
The cliff along the Madhumati River at Tejpur. Note the position of volcanic ash unit. (A) distant view, (B) close view (after Raj et al., 2008).
The Toba volcanic event is one of the largest eruptions during the Quaternary period (Schultz et al., 2002). This volcanic mega-eruption (Rose and Chesner, 1987, 1990; Knight et al., 1986; Acharyya and Basu, 1993) took place some 70,000 years ago in the northern Sumatra within the Indonesian archipelago, when a major shift was taking place in global climate from the interglacial marine isotopic stage (MIS) 5 to glacial MIS 4 (Ninkovich et al., 1978). This Toba volcanic event was more than two orders of magnitude larger than any historical eruption, and produced at least 3000 km2 of dense rock-equivalent rhyolite magma \((7 \times 10^{15})\) and more than 800 km3 of ash (Viseras and Fernandez, 1995). It is estimated that at least 1% of the Earth was covered by more than 10 cm of ash known as Youngest Toba Tuff (YTT). A widespread occurrence of tephra bed is reported, e.g., from the eastern and the western parts of the Indian subcontinent (Acharyya and Basu, 1993; Ninkovich et al., 1978; Chesner et al., 1991), the Arabian Sea (Schultz et al., 1998), the Indian Ocean (Pattan et al., 1999) and the South China Sea (Buhring et al., 2000; Song et al., 2000). The Toba event is believed to have affected the global climate system (Singurdsson, 1990). It might have also been responsible for the shift to glacial climate (Chesner et al., 1991; Rampino and Self, 1992, 1993).

Fig. 25.

SEM photographs (after Raj et al., 2008) of the volcanic ash deposit. (A) Glass shard showing typical conchoidal fracture. (B) Light, porous pumice shard consisting of parallel vesicles seen as long stretched thin capillary tube. (C) Shard showing tri-radiate junction wall of three bubbles. (D) Glass shard of different size and shape showing smooth and conchoidal surface.
Stop 4: Karjan Dam Section

Karjan River is a major tributary of the Narmada River, and has the largest tributary drainage basin within the lower Narmada basin. The effect of the ENE-WSW trending NSF is evident in the upland zone of the river where the basaltic flows are tilted southward. The stream course is not only controlled by the NSF, but also by the NNW-SSE trending Karjan Fault, especially in the alluvial zone (Fig. 13). Activities along the Karjan Fault make the basin asymmetrical, tilting it towards the west.

In the upland area of the Karjan River southward-dipping basaltic flows could be seen. The dipping flows represent part of the tilted block that is attributed to the tectonic movements along the NSF. Exposed section reveals a terrace surface at a height of 58 m from the present-day channel (Fig. 26). The sediments are dominantly sand and silty sand deposits. Calcite sheets and nodules occur in the middle of the section. OSL dating of the upper silty sand layer has yielded a date of 32.7±3.9 Ka (Fig. 26).

On the basis of sediment fabric, grain size and lithofacies association, the exposed sediments at Karjan Dam site can be correlated with the sediments in the downstream. However, there is a significant difference between the altitudes at which sediments are exposed, which could be attributes to displacement along the NSF during the Early Holocene time (Chamyal et al., 2002).

Fig. 26. Cliff on the right bank of Karjan River near Karjan Dam. Arrow indicates downstream direction of the river. Note the elevation of late Quaternary sediments above the incised bedrock comprising basaltic flows of Deccan Trap Formation.
Day 5: 16/11/2017
Vadodara to Tavra, Bharuch, Raniour, Karad and back to Vadodara
Departure by Flight to New Delhi
Stay at New Delhi.

The estuarine zone of the Narmada River may not be as large as that of the Ganga or the Brahmaputra, but is interesting, nevertheless. A visit to some of the sites along the narrow estuary will help to appreciate the geomorphic processes interacting in the area over the millennia. We first provide a short overview of the characteristics of sedimentary sequences along the estuary and their depositional environment.

**Estuarine Sequences of the Narmada River**

The sediments comprising the valley fill terrace surface ($S_2$) are exposed in 5-10 m high incised cliffs in the lower Narmada basin. These comprise two lithofacies, the tidal estuarine facies in the lower reaches and the fluvial sand facies in the upper reaches. The tidal estuarine facies is dominated by tidal carbonaceous mud with intervening fine to medium estuarine sand, showing parallel lamination. Micro-palaeontological investigations on the muddy horizons have yielded a rich assemblage of shallow marine foraminifers (Chamyal et al., 2002). The sands show ripple and cross-stratification with abundant mud laminae, flasers and drapes. The sands also show parallel bedding and bi-directional cross-stratification. Overall, the estuarine terrace sequence is dominated by tidal mud, which suggests their deposition in a tide-dominated estuarine condition. Similar facies is found in the present estuary also, which is also tide-dominated (Nigam, 1984). The tripartite (coarse-fine-coarse) facies assemblage, which is characteristic of wave-dominated estuaries (Darymple et al., 1992), is not found in the sediments. In tide-dominated estuaries, the muddy sediments accumulate primarily in the tidal flats and sand marshes, while sand is deposited in the tidal channels that run along the length of the estuary (Woodroffe et al., 1989; Darymple et al., 1992). The geomorphic setting suggests that these sediments were deposited as an aggrading transgressive tidal estuarine facies, transforming the fluvial incised valley into an estuary (Chamyal et al., 2002).

Upstream of the tidal estuarine terraces, comparable fluvial terraces occur right up to the upland zone with identical geomorphic setting. These terraces mainly consist of horizontally-stratified fluvial silty sand ($Sh$). The lateral accretion surfaces are completely absent, indicating aggradation of the incised valley through vertical accretion when the lower reaches of the river were undergoing tidal estuarine sedimentation. However, the change from a fluvial to a tidal facies is not sharply defined and appears to be transitional (Chamyal et al., 2002).
Stop 1: Tavra-Bharuch Section
At Tavra, an 8 m Holocene section, comprising estuarine sediments, is exposed along the Narmada River. It extends downstream up to Bharuch. The 0.5 m thick clay at the base is dark in colour and is rich in organic materials. This is overlain by 4 cm of sandy layer in the form of a lens, over which a silty clay bed (1.2 m) is exposed. An organic-rich clay deposit occurs above it for 3.5 m thickness, and is overlain by a 15 cm lens of sandy silt. This is followed upwards by a dark, organic-rich laminated clay for 20 cm. The laminated clay is overlain by 30 cm of brownish silty clay, over which another laminated clay band of 20 cm thickness occurs. Over this clay bed occurs a 67 cm thick silty clay bed. Above the silty clay 11 cm of clay is exposed. This is overlain by 4 cm layer of silt and over it a 15 cm of clay. A 1.2 cm of dark organic rich laminated clay, dark brown to blackish in colour overlies the thin clay layers. This is overlain by silty sand (1.25 m). The top 45 cm is marked by sand.

Stop 2: Ranipura Section
The terrace deposits along the lower Narmada valley are generally 3-4 m thick. They are mainly composed of weakly-laminated sand and silt with intermittent thin clay layers and organic inter-stratifications. The valley carries water periodically, especially during the SW monsoon. Incision has led to the formation of the terrace, which currently is inundated during high-magnitude flood events. Therefore, erosion and reworking of terrace sediments and organic material cannot be ruled out. On the basis of stratigraphic and sedimentological characteristics, Alpa Sridhar et al. (2015) divided these terrace deposits into four units: U-I (lowermost), U-II, U-III and U-IV (uppermost). The lowermost unit U-I (430-460 cm) is dominantly composed of grey medium to coarse sand (96%), with thin horizons of finer sediments (60% silt, 40% clay), and the base is not exposed (Fig. 27). No sedimentary structure is seen, and very little organic matter is present. U-II is a 115 cm thick, laterally continuous layer consisting of finely-laminated silt and clay. The contact between U-I and U-II is sharp. The bottom 65 cm of U-II comprises predominantly of black organic-rich clayey horizons with intermittent millimetre-scale silt bands. This is overlain by 50 cm thick inter-layered sand and silt horizon with fine, brownish organic-rich sediment, abundant rootlets, leaf and woody debris, including tree stumps. These layers show mottling and blocky character due to oxidation and fluctuating water levels. The silt fraction is ~55%. This organic-rich unit is overlain by U-III, the thickest unit (~240 cm), with an abrupt contact with U-II. The sediments are brown to yellow and partially pedogenized, showing a typical blocky character. The layers are faintly laminated and occur as fine sand and silt couplets. In the lower half of the unit, the sediments are composed of 3-8% sand, 50-60% silt and 37-42% clay, indicating an overall dominance of silt. In the upper half, clay content increases significantly (up to 50%) at the expense of silt. U-IV (~70 cm), the uppermost part, has centimetre-scale sand and
Fig. 27.
(A) Generalized litholog of the late Holocene terrace sediments exposed at Ranipura showing four distinct units. Also shown are the close views of (B) the section showing unit II, III and IV, (C) woody debris-rich upper part of unit II, and (D) organic matter-rich black clay in the lower part of unit II (after Alpa Sridhar et al., 2015).
silt laminations, without any organic-rich horizon. The unit is weakly pedogenized and highly bioturbated.

On the basis of proxy data and chronology, four climatic phases (I-IV) during the last two millennia have been interpreted (Alpa Sridhar et al, 2015). The first phase (prior to 2185 cal BP) has been inferred as a wet phase under a strong monsoon regime (Fig. 28). The coarser sediments and the negligible palynomorph yield during this phase indicate deposition under a high-energy fluvial condition, possibly a stream channel environment. During phase II, ~2200-1800 cal BP, low precipitation and related reduction in sediment influx resulted in enhanced tidal conditions and a wider than present estuary. During phase III, the sediment influx increased, along with enhanced monsoon precipitation. During phase IV, the sediments were deposited in stagnant water in a freshwater back-swamp with intermittent oxidizing and reducing conditions and fluctuating water table conditions.

All through, the sediments were deposited as fine sand and silt couplets, often with algal cysts and well-preserved organic matter derived from the cuticles of higher land plants. These are indicative of proximal depositional environment, rapid burial, and good accommodation potential, as supported by the chronological results. The present-day environment is facilitating multiple flooding events within a short time span. Construction of a depositional model of the Narmada lowland during the late Holocene period reveals a gradual strengthening of southwest monsoon after ~3500 BC.
cal BP, with a short pulse of dry climatic condition (~3238 - ~2709 cal BP). This was followed by climate somewhat similar to the present. Marine inundation of the lowland by sea water took place between ~2000 and 1800 cal BP, leading to tidal marsh conditions. This was followed by withdrawal of the tidal condition and large terrestrial sediment influx between 1692 and 1487 cal BP, which is coeval with a wet phase.

**Stop 3: Palaeo-bank of Narmada River near Karad**

In the westernmost part, the NSF is represented by steep escarpments along the Tertiary highlands, whereas further west it is expressed as a palaeo-bank of the Narmada River. The entire Tertiary sequence is folded and faulted. In this segment, the exposed Tertiaries exhibit linear anticlinal structure, trending SW to WSW, plunging SW to WSW and flanked by reverse faults along the southern limbs. The Tertiary sequence ranges in age from Paleocene to Mio-Pliocene, and is dominated by rudaceous to calcareous facies and highly ferruginous, cyclic sedimentation of calcareous sandstone and marls, calcareous clays, formainiferal limestone and fossiliferous beds.

The palaeo-bank at Karad is marked by straight linear alluvial cliffs formed in the Quaternary sediments. It is formed by the migration of Narmada River to the NW to its present course, and represents an abandoned left bank of the river when it was flowing further to the SE. Since then the river has migrated by about 6 km to the NW, especially due to tilting caused by the upliftment of the Jhagadia-Ankleshwar area. The linearity of the feature suggests the presence of a fault along this palaeo-bank. Previous seismic studies suggested the presence of reverse fault along the palaeo-bank with the down-throw side to the NW and the upthrow side to the SE side (Agarwal et al., 1986).
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Geomorphological Field Guide Book

on

TAMILNADU COAST

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Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
### Geomorphological Field Guide Book on Tamil Nadu Coast

#### Itinerary

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A. TAMIL NADU COAST: AN INTRODUCTION

Sea coast is one fascinating area where man interacts with Nature for a large number of activities on daily basis. Considering the coastal environment as a Common Property Resource (CPR), human societies have started using the different facets of coastal landforms for numerous kinds of activities, and without any restriction. This has resulted in several types of land degradation along some of the coasts, with implications for socio-economic activities along them. Even otherwise, the coastal strip is an assemblage of several dynamic landforms, resulting from the actions of marine, estuarine, aeolian and fluvial processes, etc. Observation of these landforms and interpretation of data collected from them provide us insight to their origin and evolutionary trends, as well as the processes involved in their making and the likely changes in them under induced pressures. In view of this, it is important to study, record, document and disseminate all the physical and socio-cultural details of the coastal belts, as well as the resource potentials of the coastal tracts and their vulnerabilities to pressures. Such studies at suitable spatial and temporal scales can help proper use, management and conservation of the coastal belts. It is important to apply certain standards for the use of coastal CPR, so that it can sustain its attractiveness through improved management. India has a coastline of about 7,800 km, but in many areas the coast is now under a phase of vigorous erosion and subjected to adverse changes. The length of the coastline in Tamil Nadu state is about 1076 km.

Weather and Climate

Tamil Nadu, as also the rest of India, is dominated by monsoon climate. The normal annual rainfall of the state is about 945 mm. Unlike north India, which receives its maximum rainfall during the period of Southwest monsoon, large parts of south India, including Tamil Nadu state, receives almost half of its rainfall during the Northeast monsoon. The state, in fact, has three distinct periods of rainfall. About 48% of the total annual rainfall is received from the Northeast monsoon (in November-January), 32% from the Southwest monsoon (mostly in June-September), and the rest during the retreat of the Southwest monsoon in October, when tropical cyclones emerging in the neighbourhoods of the Andaman Islands bring some rains (October to mid-November). The dry season is from the end of February to June.

The hot weather begins in mid-March and lasts till June. The hot winds start blowing from April, with an average velocity of 8–16 km/hour. The highest temperature is often registered in May, when different meteorological stations often record a maximum of 40-45°C. From June onwards the humidity increases significantly, which increases the discomfort level manifold due to the hot weather. The cold weather commences early in October and comes to an end in the middle of January. The climate during cold weather is pleasant. The days are bright and warm but the
sun is not too hot. As soon as the sun sets, the temperature falls, and makes it more comfortable.

Since the state is entirely dependent on rainfall for recharging its water resources, monsoon failure leads to acute water scarcity and severe drought. Tamil Nadu is classified into seven agro-climatic zones: north-east, north-west, west, southern, hilly (high altitude; high rainfall), and Cauvery Delta (the most fertile agricultural zone). Southern Tamil Nadu is usually more dry than the northern part, necessitating the construction of thousands of tanks for drinking and irrigation purposes. The Ramanathapuram-Tirunelveli coastal segment is one of the driest areas.

Geology and Geomorphology of the Tamil Nadu Coast

Geology

The southern part of Tamil Nadu state, which includes the coastal tracts to be visited, has three major lithostratigraphic units. Major part of the area comprises Precambrian granitic rocks, charnockites, granulitic retrograded products and basic intrusive, which are overlain by the Tertiary calcareous sandstone and recent coastal sediments. During the Proterozoic, several major shear zones dissected the granulitic terrain, and the granulitic facies assemblages suffered retrogradation. The crystalline charnockitic rocks are exposed in the western part of Ramanathapuram district and adjacent areas (Chandrasekar et al., 2005). In Kudankulam area, foliations are very distinct, and at places of weathering charnockites, biotite and garnet have become segregated along the foliated planes.

Coastal tectonics of Southeast coast of Tamil Nadu: In the tectonically active coastal tracts, marine notches are considered as one of the indicators of rates and pattern of uplift. Indian coasts are subjected to tectonic movement in the Quaternary period. A simplified tectonic map of southern Tamil Nadu and Kerala, as well as a map of the types of major faults aptly summarises the geology of the area (Fig. 2; after Drury et al., 1984).

Fig. 2. Tectonic features of southern Tamil Nadu and Kerala.
Based on the variations in landforms and occurrence of lineaments, the southeastern coast of Tamil Nadu between Rameswaram and Kanyakumari has been classified into seven major blocks. It has been suggested that the seven blocks form the planes of weaknesses and cause the continuity of strike slip faults along the lineaments. The sharp triangular shape of Rameswaram Island might have some genetic link with tectonic activities during its evolutionary stages, especially the activities of the Vaigai Fault. Loveson et al. (1996) identified the following major blocks: (1) Mandapam – Valinockam block, (2) Valinockam – Vaippar block, (3) Vaippar – Thiruchendur block, (4) Thiruchendur – Navaladi block, and (5) Navaladi – Kanyakumari block (Dajkumar et al., 2015).

A study by Chandramohan et al. (2001) has revealed that the average annual rate of sediment deposition in the shallow marine shelf areas adjoining the Tamil Nadu coast is 0.01 m in Gulf of Mannar, 0.006 m in Pak Bay, and 0.003 m at Sand Heads. The study also reveals that the sands are coarse to fine grained, and the fineness increases towards Kovalam (between Chennai and Kalapakkam), possibly due to higher fluvial deposition in that direction.

Coastal Geomorphology of Southern Tamil Nadu

The coastal tract of southern Tamil Nadu extends for about 1075 km from Pazhaverkadu in Thiruvarur district to Ezhudesam in Kanniyakumari district. Kanniyakumari forms the southernmost tip of the Indian subcontinent where Indian Ocean, Bay of Bengal and Arabian Sea meet. Pamban Island and Rameswaram form part of the Ramanathapuram district, separating Gulf of Mannar and Palk strait from Sri Lanka, except a string of tiny islands called the Ram Setu (earlier known as Adam’s Bridge).

About 46 streams originating from the hilly Pre-Cambrian granite-gneiss terrain of the Eastern Ghats and the Nilgiris drain through the Tamil Nadu coast to meet the Bay of Bengal through small estuaries and lagoons. Among these, six are the major ones. The streams are the Palar, the Cauvery, the Vaigai, the Vaippar, the Tambaraparani and the Nambiyar. Apart from the Cauvery, which has a wide deltaic plain with appreciable sedimentary contribution of alluvium, all the other streams have smaller sedimentary loads along them, and narrower associated plains. The sandy beaches are dominant especially along the coast near Ennore, Chennai, Mahabalipuram, Manakkanam-Pondichery, Cuddalore, Rameswaram, where fine to medium sand is mixed with broken shell fragments, shingles, etc. In the southern part, the beaches at Vattakatti, Rasthakadu, Muttam, etc., have high percentage of black sand, especially consisting of heavy minerals like monazite, garnet, ilmenite, magnetite, etc. Coral reefs are numerous in Pamban-Rameswaram-Palk Bay sector, where several small islands (Tivus) have reefs of thriving coral colonies. The coastal tract of Pichavaram (near Cuddalore), Vedaranyam, Pt. Calimere, Muttipet and Tuticorin have mangrove forests along a muddy coast. A number of lagoons, fronted by spit, have also developed along the coast. The largest of the lagoons is at Pulicot,
which is the second-largest lagoon in India. Overall, the coastline along Tamil Nadu is straight and narrow, except near Vedaranyam where the coastline takes a sharp westward turn and becomes indented. The mean sediment drift appears to be from south to north, as the Northeast Monsoon (November-January) is more vigorous along this coast than the Southwest Monsoon (June-September). Littoral drift during the Southwest monsoon is weak.

The southeastern coast of Tamil Nadu provides numerous examples of erosional and depositional landforms. Among the depositional landforms, prominent features are beach ridges, swales, spits, and estuaries. The major erosional landforms are wave-cut platforms, cliffs, marine terraces, sea caves, etc., which can be seen in and around Rameswaram, Mandapam, Valinokkam, Kannirajapuram, Thiruchendur, Manapad, Idinthakarai and Kanyakumari (Chandrasekar et al., 2005). At places, marine notches have developed in coastal beach rocks that run parallel to the coast. Beach grooves, containing rock outcrops and exposures with fossil assemblages, are also exposed along the present strand lines (Fig. 3). Coastal cliff rocks at places provide signatures of palaeoclimate and the prevalence of past shallow marine environmental conditions, as attested by a series of eight beach ridges in curvi-linear fashion between Mandapam and Valinokkam, as well as 2-3 well developed sub-ridges. All these beach ridges occur sub-parallel to the present coastline.

Fig. 3. Landforms along the Tamil Nadu coast.

**Tsunami and Cyclone effects:** The devastating Indian Ocean Tsunami that was generated after a major 9 Mw earthquake near Banda Ache in Indonesia on 26
December 2004, caused not only loss of humans and properties along the coast of Tamil Nadu, but also modified the coastal landforms to some extent. Nagapattinam coast was most severely affected, where the maximum water level rose to 4-5 m, and the inundation reached 3 km inland. The beaches became flatter as the backwash of the plunging waves swept away the smaller undulations of backshore region. The sediments at many places became enriched with re-worked foraminifera fragments, which led researchers to assume that a palaeo-strandline, now at a depth of 30-40 m in the sea in shallow shelf region, was exploited by the tsunami waves to bring up the fragments. At places the beaches also became enriched with heavy minerals.

The inundation was more in the areas between the fore dunes and the back dunes, and the waves swept away most of the temporary hutsments of fishermen in between the two dune systems. About 700 persons died in Nagapattinam district, followed by 250 in Kanyakumari district and 200 in Cuddalore district. About 125 persons perished in the state capital, Chennai. In Kerala, 86 persons were reported as dead, out of which 67 death was reported from Kollam district and 16 from Alappuzha district. Hundreds of people were also injured and many livestocks perished as seawater surged through the fishing hamlets and entered the village settlements. The previous notable tsunami along this coast was recorded during 1881 as the consequence of a major earthquake in the Andaman Islands.

Apart from the tsunamis, the coastal configuration and the life and properties in coastal zones are also greatly affected by the cyclones. Several cyclones, originating in the Indian Ocean or in the Bay of Bengal, regularly sweep across the Tamil Nadu coast, their average number per year being 16. The large waves generated during the Super Cyclone of 1999, as well as the accompanying strong winds, modified the beaches to a large extent, while the gusts of wind and the incessant rains caused extensive damage to life and properties in the coastal belt and inland areas of Tamil Nadu.

**Socio-economic Aspects**

There are 13 districts in Tamil Nadu that share the coastline. These are: Thiruvallur, Chennai, Kanchipuram, Villupuram, Cuddalore, Thiruvurur, Nagapattinam, Thanjavur, Pudukottai, Ramanathapuram, Thoothukudi, Tirunelveli and Kanyakumari. About 300 villages and 25 urban centres thrive on the land resources of the coastal resources of these districts. The density of population is more than 400 per square kilometer, which is high. Among the coastal towns and cities, Chennai is a megalopolis, with several smaller town clusters around it. Tuticorin-Tiruchendur, Thiruvottiyur-Pulicot, Cuddalore-Portonovo, Nagapattinam, Rameswaram-Mandapam, Vedaranyam and Kanyakumari are the other major urban centres. All these urban centres are currently witnessing moderate to high population growth, driven especially by expansion of trade and commerce, as well as in marine salt-based industries and fishing, while some are also witnessing considerable tourist influx (e.g., Mamallapuram, Poompuhar, Nagore, Rameswaram-Mandapam,
Tiruchendur, Kanyakumari). Chennai and some major cities are also engaged in harbour works, oil refineries and associated chemical industries like fertilizer, pesticide, as well as pharmaceuticals, etc. The coastal towns and cities inhabit roughly 6 million people, which account for about 10% of the total urban population of the state.

The rural land use is dominated by agriculture, where the croplands occupy more than 40% of the total coastal area. Sand dunes with or without vegetation, salt marshes, mangroves, as well as barren rocky areas, which together cover a class of land use traditionally termed as ‘wastelands’, cover about 4% area.

The state has a fishermen population of 1.05 million. The coast consists of 3 major fishing harbors, 3 medium fishing harbors and 363 fish landing centers. The marine fishing output from the state contributes to 10-12% of the total marine fish production in India, which is estimated at 0.72 million tonnes. Aquaculture includes shrimp, sea weed, mussel, clam and oyster farming.

Tamil Nadu has four major sea ports at Chennai, Ennore, Tuticorin and Nagapattinam. There are 11 other minor ports. Chennai Port is an artificial harbor and is India's second busiest container hub. Because of its shallow waters, Sethusamudram, the sea separating Sri Lanka from India, presents a hindrance to navigation through the Palk Strait. Though trade across the India-Sri Lanka divide has been active since at least the first millennium BCE, it has been limited to small boats and dinghies.

The coast of Tamil Nadu was along the ancient Silk Route and, hence, played an important role in spice trade with the western empires. Roman and Greek traders frequented the ancient Tamil country, securing trade with the sea-faring Tamil states of the Pandyan, Chola and Chera dynasties. Since the time of the Ptolemaic dynasty (i.e., a few decades before the start of the Common Era) the traders established trading settlements along the coast to strengthen trade between South Asia and the Greco-Roman empires. Even after the fall of those empires, the trading continued due to the operations from the settlements. Major ports included Uraiyur, Korkai, Poompuhar and Kaveripattinam. The ancient city of Poompuhar was destroyed by the sea around 300 BC.

During the reign of Raja Raja Chola I and his successors Rajendra Chola I, Virarajendra Chola and Kulothunga Chola I, the armies of the Chola Dynasty invaded Sri Lanka, Maldives and some parts of Malaysia, Indonesia and southern Thailand (Sri Vijaya Empire), especially in the 11th Century. In 1025, Rajendra Chola launched naval attacks on the ports of Srivijaya and against the Burmese kingdom of Pegu. Through this operation he conquered parts of Malaysia and Indonesia and Thailand and occupied the areas for some time.
Fig. 4. Tamil Nadu state, showing major sites to be visited.
B. DESCRIPTION OF THE FIELD SITES

The field visit will begin at Chennai in Tamil Nadu state and end at Thiruvananthapuram in Kerala state. The major sites proposed for visit are shown in Fig. 4.

Day 1
Arrival at Chennai
Stay at Chennai.

The first day will be spent on briefing about the field visit and a short visit to Chennai’s Marina Beach.

Day 2
Chennai to Velankanni
Stay at Velankanni.

On day-2, the coastal features between Chennai and Velankanni will be explored. The coastal tract from Chennai southward is also known as Coromandal Coast. Following is a description of the sites to be visited.

Stop 1: Mahabalipuram Beach

Mahabalipuram beach is located 58 km to the south of Chennai, lying at the shore of Bay of Bengal (Fig. 5). This 20 km long beach came into notice for tourism purpose during the 20th Century. The beach is thronged by tourists mainly during the months of November and February.

Fig. 5. Mahabalipuram beach.
Beach morphology: Beaches, beach ridges, backwaters, mudflats, palaeo-tidal flats and palaeo-barriers form the coastal landscape at Mahabalipuram. These landforms are bordered in the west by Mio-Pliocene Cuddalore Sandstone and the pediplains developed in the Charnockites of Archaean era. The prevalent wave action and the large amount of sediments derived by littoral currents make the beaches highly dynamic. Although beach accretion is noticed along the entire length of the coast, erosion is also observed around Ennore. Two beach ridges can be observed along many parts of the coast, which exhibit strandline characteristics. The maximum height of these beach ridges is 5 m above MSL.

Panoramic view of the sculptures: Mahabalipuram is an ancient historical town. It has a group of beautifully carved structures in granite, which were carved out from a single rock in 7th Century AD, especially during the reign of King Mahendravarma I and his son Narasimhavarman I (630–680 AD; also known as “Mamalla”, the Great Warrior) of the Pallava Kingdom (Fig. 6). These monuments are an example of the age-old monolithic rock-cut architecture of India, and are now a part of the UNESCO World Heritage sites, providing excellent exposure to the Pallava Art. Archaeology Survey of India (ASI) maintains the edifices.

Fig. 6. Panoramic view of the sculptures at Mahabalipuram.

The monuments are mostly cut along the faces of a cliff and are monolithic, constituting the early stages of Dravidian architecture wherein Buddhist elements of design are prominently visible. The intricately designed edifices include Rathas (temples in the form of chariots), Mandapas (cave sanctuaries), and giant open-air relief. The pillars are of the Dravidian order. Although sometimes mistakenly referred to as temples dedicated to the five kings of Pandava clan in the epic Mahabharata, namely, Yudhishtira, Bhima, Arjuna, Nakula and Sahadeva – and their common wife, Draupadi, the structures were never consecrated because they were never completed, and were left un-finished after the death of Narasimhavarman (Fig. 7).

It is believed by some experts that this area served as a school for young sculptors. The different sculptures, some half finished, might have been examples of different styles of architecture, and were probably sculpted by the young students as per demonstration by their instructors. This can be guessed from the sculpture “Pancha
Rathas” (five chariots), where each Ratha is sculpted in a different style, although all the five were carved out of a single piece of in situ granite. The carvings at Mahabalipuram might have required hundreds of skilled sculptors (Iniyan, 2015).

Fig. 7. A glimpse of the Pancha Ratha (five chariots) at Mahabalipuram.

The tsunami of 26th December 2004, although a devastating one, exposed some beautifully carved structures in the near-shore zone of Mahabalipuram, especially as the backwash from the tsunami waves scooped out considerable thickness of sand from the lower beach. The structures included a granite lion and an elephant relief. Mahabalipuram beach is also famous for activities like sunbathing, diving, wind surfing and motor boating (https://en.wikipedia).

**Stop 2: Dansborg Fort in Tarangampadi**

Tharangambadi, located in the southeast of Tamil Nadu, is famous for its 17th Century Danish fort with a breathtaking view of the Bay of Bengal (Fig. 8). The site is still largely unspoiled by destructive tourism, and retains its natural scenic beauty due to less crowding.

Fig. 8. Dansborg Fort and Bungalow on the beach at Tharangambadi.

The Fort Dansborg was built in 1620 by Ove Gjedde, Commander of the Royal Danish Navy, when he was 26 years old. The Fort was built on the orders
from Danish King Christian IV of Denmark and Norway. A treaty was signed on November 20, 1620 between King Raghunatha Nayak of Thanjavur and the King of Denmark, by which the Danes were given permission to build the Fort at Tharangambadi (Tranquebar) for trading. The Fort faces the Bay of Bengal and the sea is just 200 m from the Fort.

The Fort has two levels. The lower level was used to accommodate soldiers and horses, as also to store materials used for trading and as a prison. The upper level was used as residence of the governor and the priests. Presently, a museum at this upper level exhibits Danish era artifacts at Tharangambadi. Although Tharangambadi was a busy port during the 17th century, it is no more a port now. Some fishing activity can, however, be noticed.

**Stop 3: Poompuhar Beach**

The coastline between Nagapattinam and Poompuhar is almost straight with a high energy zone at a depth of 8 to 9 m (Jeena et al., 2001). Poompuhar is an ancient port city, and was built on the north bank of Cauveri River, close to the site where the river flows into the sea. Its beach is often crowded with local tourists (Fig. 9). Puhar in Tamil language means an estuary. This ancient port city used to be called earlier as Kaveri Poompattinam, and was the capital of the early Chola rulers. The town had two distinct clusters, Maruvurpakkam near the sea and Pattinappakkam to its west (Iniyan, 2015). These two clusters were separated by a stretch of gardens and orchards where daily markets used to be held under the shade of trees. The market place was known as ‘Naalangadi’ during the day and as ‘Allangadi’ by night. It is learnt from ancient literature that Maruvurpakkam was near to the beach and had several terraced mansions and warehouses with windows shaped like the eyes of the deer.

![Fig. 9. The Poompuhar beach.](image)

The ancient town was destroyed by the sea and was submerged, presumably in 500 AD. It was rebuilt thereafter. According to the National Institute of Marine Archaeology, much of the town was washed away by progressive erosion of the sea and by floods. Ancient pottery and figurines dating back to the 4th Century AD were recently found by ASI during some excavations. Submerged wharves and lengths of
pier walls have also been excavated in recent times. The findings confirm the antiquity of the town as found from literary sources (Sundaresh et al., 2004).

Buddhism flourished in Poompuhar two thousand years ago. Some pillars erected during the 2nd Century BC have inscribed on them “Kangitha Somaya Pikunia Thanam”, meaning “this pillar was donated by Somaya Pikkuni of Poompuhar”. Two other tourist attractions at Poompuhar are: (1) the Masilamani Nathar Koil, which was built in 1305 by Maravarma Kulasekara Pandiyan, and which bore the sea erosion; and (2) a seven-storied structure called the Silapathigram Art Gallery that focuses on Sangam literature. Poompuhar is known as the oldest continuously inhabited place in Tamil Nadu.

Day 3
Velankanni to Tuticorin
Stay at Tuticorin.

Stop 1: Rameswaram - Ancient Coral Reef Terraces

Rameshwaram, a strategically and socially important island along the east coast of India, is excellent for the study of coastal evolution during the Quaternary period. The island has landforms like beaches, beach ridges, mudflats, raised coral terraces, lagoons, spits, etc., along with living corals (Fig. 10). The evolution of coastal landforms could very well be reconstructed through integration of the landform distribution with the available carbon-14 dates. There are indications that sea level has played a major role in the evolution of landforms in the island. The raised terraces that are dated to 125000 years BP were formed as fringing reefs during that period. The emerged reef-corals during the subsequent regressive phase of the sea served as places for marine sedimentation, as indicated by the mudflats and beach ridges of later period. The spit is a recently-formed landform in the island (Rajamanickam and Loveson, 1990).

Marine/ coral reef terraces: In the northeast of the island the beaches get terminated by a cliff, which is formed of coral reefs as well as exposed Cuddalore Sandstone, both appearing along a terraced landform. The marine terraces are exposed at few places in the island. Commonly, the terraces are composed of corals with calcareous, evaporite deposits; the deposits get easily eroded by sea wave to form sea caves and notches along the Mandapam coast. The average height of the exposed terraces is about 3.5 to 3.8 m (Chandrasekar et al., 2002). The mineralogical composition in the northern sector differs from that in the eastern sector. Near Valinockam the notches are well-developed, and are made up of consolidated hardened sandstone. The Rameswaram Group of sediments was deposited under marine condition more than 28,000 years before present (BP). Probably between 12,000 and 18,000 years ago the bottom part of the deposits got elevated to a level of the present beach line. Marine terraces located at Valinockam, south of Mandapam, are made up of calcareous sandstone and are significantly covered by sand dunes.
(Krishnakumar et al., 2011). In this terrace, hard marine calcareous sandstones, comprised of heavy and light minerals, are observed. The rounded notches are developed above the mean sea level due to wind activities. In this sector, two marine transgression and regression took place within a short period of 30,000 years.

![Geomorphological map of Rameswaram](image)

**Fig. 10.** Geomorphological map of Rameswaram.

**Stop 2: Dhanushkodi Sandpit (Emerged Coast)**

Dhanushkodi has the only land border between India and Sri Lanka, and is one of the smallest international boundaries in the world (45.7 m in length), located on a shoal in Palk Strait. A number of small, emerging spits can be identified near the land’s end at Dhanushkodi (Fig. 11). Beyond lies a group of tiny coral islands, arranged almost linearly in a roughly WNW-ESE direction, which together are known as Ram Setu (also called the Adam’s Bridge), and lead to the land’s end of Sri Lanka at Talaimannar (Fig. 12).
Before the 1964 cyclone, Dhanushkodi was a flourishing tourist and pilgrimage town. It had then a railway station, a small railway hospital, a higher secondary school, a post office, customs and port offices, etc. The 1964-cyclone swept away a part of the railway tracks at Dhanushkodi. A number of buildings in the southern
part of Dhanushkodi, including some temples, also got submerged in the sea. In 1965, the town was declared unfit for habitation. At present only a small group of fisher folks resides in Dhanushkodi. Haunting yet appealing, deserted but still full of life, eerie but fascinating, Dhanushkodi, with a population of less than 500, attracts many tourists (Fig. 13). Its breathtaking natural beauty, away from the worldly connections (the nearest telephone booth is about 20 km away), makes it a place truly less-travelled (https://en.wikipedia).

**Stop 3: Mandapam Beach**

The coastal landforms between Devipattinam and Mandapam can be grouped under depositional and erosional features. Sandy beaches and rocky beaches are dominant between Mandapam and Rameswaram. At Mandapam rocky beaches abound (Fig. 14). The lush green vegetation seen on the hills beyond the Bay of Bengal here is on the Eastern Ghats (Fig. 15). The rocky beach hosts a rich marine fauna, including live corals (Fig. 16).

Fig. 14. A shallow rocky beach at Mandapam, with breaker waves at a distance.

Fig. 15. Another view of the rocky beach at Mandapam.

Fig. 16. Corals forming a part of the rocky beach at Mandapam.
For people interested to see the life in the shallow sea beyond Mandapam, the Forest Department of Tamil Nadu runs the services of some glass-bottomed boats. These allow the tourists to see beautiful coral reefs and even live corals under the sea, as well as numerous other fauna and flora. An amusement park along the Mandapam beach, measuring about 16 ha, keeps the children engaged, as it is home to man-made coral reefs, fountains and hillocks.

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**Day 4**

**Tuticorin to Kanyakumari**

**Stay at Kanyakumari.**

**Stop 1: Tiruchendur Beach and Sea Caves**

Tiruchendur is situated in Thoothukudi district of Tamil Nadu, and provides a glimpse of the Gulf of Mannar and the Indian Ocean. It has a narrow sandy beach, which is steeper (about 3-6 degree) than in areas further north (1-3 degrees), followed seaward by rocky shore platforms (Fig. 17). The shore platforms mostly occur in between the low tide and the high tide, and are formed of marine calcareous sandstone, rich in quartz and felspar, with embedded Mollusc shells. At Tiruchendur, the older shore platforms/beach ridges could also be found several meters above the mean tide level.

**Fig. 17. The sandy beach at Tiruchendur, followed sea-ward by rock platforms.**

At least four strand levels could be identified, the highest and the oldest occurring at about 12 m above MSL. It suggests that the relative Holocene sea level along this coast probably dropped after the cementation of the sand, although some tectonic effects might also be involved (Chandrasekar, 2001). Abundance of fine to medium sand along this beach suggests a low wave energy environment. The original beach topography has become modified due to the construction of a number of edifices around an old temple on the beach (Fig. 18). Another old temple at the base of a sea cliff near by, occurs in a cave (Fig. 19). This cave has also been modified over the last few centuries, and it is difficult to establish if the cave was formed naturally by sea waves. The coastline south of Rameswaram was less affected by the Tsunami of 2004, especially because of the shelter effect of Sri Lanka landmass. At Tiruchendur
the overall change in beach volume due to the tsunami was estimated as net accretion of 0.48 cubic m, while at Manapad, about 18 km to the south, it was estimated as net erosion of 1.50 cubic m. A longer record of observations along the two coasts, from 1979 to 1988, showed a net accretion rate of 4 m per year at Tiruchendur and a net erosion rate of 8 m per year at Manapad (Natesan and Subramanian, 1994).

As mentioned above, the narrow shore at Tiruchendur is famous for an ancient temple dedicated to Lord Muruga, which attracts huge crowd of devotees. The earliest inscription in the temple has been dated to 875 AD. Another temple nearby, known as Valli’s Cave or Dattatreya’s Cave, is located in a cave at the base of the sandstone cliff on the sea shore towards the north-eastern end of the Muruga temple. This cave temple is dedicated to Goddess Valli, consort of Lord Muruga, and has several carved stone pillars. Between 1646 and 1648 the Dutch East India Company occupied Tiruchendur during a fight with the Portuguese who had colonised the area earlier. The Dutch started living in the temple, and while vacating it, carried some of the idols and threw them in to the sea. The idols could be fished out after some years. The temple was re-built in 1868.

Stop 2: Manapad

The Manapad beach, located about 18 km south of Tiruchendur, occurs along a sharp bend of the coastline around a hard crystalline massif that has resisted the smoothening of the coastline. This projection of land and a strong longshore drift northward helped the formation of a long re-curved spit with lagoon, and facilitated the formation of an excellent natural harbour (Fig. 20). Locally, the sandy beach is
wider to the south of the headland that hosts the Lighthouse, and is narrow to its north. The old beach ridges inland, the likes of which occur at Tiruchendur, have also been found to occur at Manapad. The highest one forms a terrace at 25 m above MSL. Down the slope from this terrace towards the beach, three other terraces occur at 19 m, 8 m and 3 m, and appear to lose height progressively to the north and south of the headland (Fig. 21). This is perhaps due to a local upwarping at Manapad. A similar condition is reported from the coastlines of Wellington district, New Zealand and from the coastlines of Chile, where the coastal terraces have been displaced tectonically.

![Fig. 20. Manapd Point, as seen on Google Earth image.](image1)

![Fig. 21. The Holy Cross Church at Manappad.](image2)

Manapad is famous for its association with a Christian saint, St. Francis Xavier. It is believed that he came to Manapad first in October 1542 for one year, and again in 1544 for few months, before returning to Goa. An inscription at the entrance of a small cave here tells that St. Francis Xavier used to live and pray in the cave, which was dedicated to Goddess Valli, and used earlier for meditation by a Hindu saint. A rudimentary church on the beach, built in 1540 around a Cross made from the mast of a wrecked ship by its Portuguese sailors (named as Captain’s Cross), was also used by St. Francis Xavier for his services and miracles. In 1581 the Church of the Holy Cross was built at the site of the old edifice (Fig. 22). An annual festival at the
church in September draws huge crowd of devotees. Another important tourist location is Manapad Point, which provides surfing activities.

![A coastal terrace at Manappad](image1)

**Fig. 22. A coastal terrace at Manappad.**

**Stop 3: Vattakottai Fort and Beach Morphology**

Located about 6 km NE of Kanyakumari beach, the Vattakottai Fort was built in the 18th Century as a coastal defence-fortification and barracks in the erstwhile Travancore kingdom. It was constructed under the supervision of Captain De Lannoy, an ex-Dutch naval officer of the Dutch East India Company, who became commander of the Travancore Army, after he earned the trust of the Travancore King Marthanda Varma (https://en.wikipedia). The fort is now under the protection of Archaeological Survey of India, and is guarded by a 8-9 m high wall (Fig. 23), which connected the Circular fort with the Padmanabhapuram but later this path was sealed due to various reasons. The fort provides a clear view of the Indian Ocean in the south and the Western Ghats in the north. A small river joins the sea on one side of the Vattakottai fort. The beach is rich in black sand.

![The high wall of the 18th Century Vattakottai Fort](image2)

**Fig. 23. The high wall of the 18th Century Vattakottai Fort.**
Day 5
Kanyakumari to Inayam and back to Kanyakumari
Stay at Kanyakumari.

Stop 1: Kanyakumari

Kanyakumari lies at the southern tip of peninsular India where the Bay of Bengal, the Indian Ocean and the Arabian Sea meet (Fig. 24). The confluence of these three places is also referred to as Thriveni Sangamam. Geographically, Kanyakumari also defines the southern end of the Coromandal Coast. The area around Kanyakumari provides numerous examples of interesting coastal geomorphological features (Fig. 25). Following is a description of the sites to be visited during the day.

Stop 2: Manakudy Estuary

Manakudy estuary is the second largest estuary in Kanyakumari district, in which the Palayar River from Mahendragiri drains. It is dominantly a sand-built estuary, connected to the sea during the rainy season (Fig. 26).

During the period of total occlusion of the river mouth the estuarine water swells due to heavy inflow of water from the head of the estuary and also by the land drainage. There is also heavy surface runoff from the paddy fields and coconut plantations into the estuary. The clay-mixed alluvium gets deposited at the mouth of the estuary.
During heavy inflow into the estuary the sand bar opens up under the force of gravity. Shallow fluvio-marine landforms like salt marshes and tidal mud flats are associated with the estuary. Other associated major landforms are the sandy beaches, rocky shores, oyster reefs, mangrove forests and small river deltas (Mujabar et al., 2011). The hills and uplands beyond are dominantly of Khondalite and Charnockite. The existing seawall, near the mouth of Palayar River is not stable, as there is considerable erosion at the tip of the seawall. This has damaged several dwelling units in the surroundings. To minimise further damage, it has been suggested to construct a groynes field for up to a distance of 1.5 km, and to raise the crest elevation of the existing seawall by 2 m.
Manakudy estuary abounds with fishery resources and has many fishing hamlets on the banks. Although there is no major industry near the estuary, three small-scale industries are well established on its banks. These are: coconut husk retting, lime shell dredging and salt works.

**Stop 3: Beaches and Sand Dunes**

Sandy beaches occur mostly in Sanguthurai, Pillaiyoppu, Rajakkamangalam, and Colachel coastal areas due to swashing of larger sediments by constructional wave actions. Rocky shores are predominant in Kanyakumari, Muttam, and Colachel areas, where the immediate inland topography is also rocky/hilly. The inshore region at these places is also rocky, which act as a natural barrier to wave actions and storm surges. The rocky boulders and sea cliffs abound in the Muttam and Kanyakumari coasts (Fig. 27, 28). Typical wave-cut notches (0.38 km$^2$) and wave-cut platforms (0.62 km$^2$) are found along the Muttam (Fig. 29, 30) and Colachel coasts where the destructive waves undercut the weaker parts of the rocky shore to form the notches and platforms. Large sand bars (0.05 km$^2$) at river mouth can be noticed in the estuary near Thengaiappattinam and Manakudi.

![Fig. 27. Beach rocks along the south-western coast of Tamil Nadu.](image-url)
Repeated field measurements at Colachel beach between 2006 and 2008 revealed the range of wave height as between 0.5 and 2.5 m, and wave period between 8 sec and 15 sec, with strong seasonal fluctuations. This has its effect on beach profile, which undergoes erosion during the SW monsoon (June-September), but regains much of the lost volume and shape by January-February. A strong westward longshore drift takes place from June to August, carrying large volume of sediments along that direction, the transport rate apparently increasing after the construction of several man-made structures. The total volume of sand transported during the 2-year measurement period was estimated as 1810 m$^3$ (Hentry et al., 2013). The sediment drift, both along and across the beach due to littoral current and high wave energy, is leading to net coastal erosion (Kaliraj et al., 2013).

The Colachel beach and the Muttam beach are also the major hosts of radioactive minerals like monazite, mixed with ilmenite and zircon (Fig. 31). The total heavy mineral content in the beach sand at Colachel is 22% by weight, while at Muttom it is 21%.

The coastal sand dunes are dominantly the parabolic dune complexes with a height of 2-4 m, especially in the Kanyakumari-Kovalam (3.27 km$^2$), Manakudi-Periyakadu (2.38 km$^2$) and Manavalakurichi-Colachel (1.30 km$^2$) tracts (Fig. 32). The backshores and the foredunes at Kovalam, Pallam, Manavalakurichi, Mandaikadu and Inayam are affected by severe erosion due to strong backwash (Fig. 33).
Kanyakumari beach is a famous tourist location, especially for the beautiful views of sunrise and sunset over the open sea (Fig. 34). Kanyakumari is also visited for the Vivekananda Memorial Rock, which is an isolated rock outcrop in the open sea, about 500 m from the land, where the Indian Saint, Swami Vivekananda had meditated, as also the colossal 40 m high statue of Thiruvalluvar in granite on the same rock outcrop, and a Memorial to Mahatma Gandhi (Gandhi Mandapam; Fig. 35). Muttam, beach is also famous tourist destination (Fig. 36).
Fig. 33. Coastal erosion between Kanyakumari and Kovalam.

Fig. 34. Sunrise at Thriveni Sangamam, Kanyakumari.

Fig. 35. Gandhi Mandapam and Thiruvalluvar statue at Kanyakumari.

Fig. 36. Muttam beach and sea resort.
Beach Placer Deposits and their Mining: The coastal tract of Tamil Nadu is known for high concentration of heavy minerals (specific gravity >2.85), mostly derived from the crystalline basement rocks. The accumulation of beach placer minerals in the coast is chiefly due to the terrestrial sources, from where the minerals are carried by water to the sea through the estuaries (Fig. 37). The source rocks are abundant in the hinterlands of the coast, making the formation of placer very easy. The total average content of heavy minerals is around 39%. Of these, ilmenite forms the major constituent (24%: Fig. 38, 39), with rutile (1.8%), leucoxene (0.9%), zircon (20%), monazite (1%), sillimanite (3.5%) and garnet (5.5%). Ilmenite contains about 56% TiO$_2$. Muttam beach has high concentration of ilmenite and monazite (Fig. 40, 41).

The monazite has a total of 58% REE oxides and 8% ThO$_2$. The total reserves of heavy minerals in the Manavalakurichi-Colachel stretch are estimated to be about 1.6 MT. Ilmenite amounts to about 1 MT. The estimated reserves of other minerals are as follows: 0.075 MT of rutile, 0.035 MT of leucoxene, 0.082 MT of zircon, 0.043 MT of monazite, 0.23 MT of garnet, 0.14 MT of sillimanite and about 6850 tonnes of kyanite.

In fact, the coastal areas of India is known to contain large amounts of heavy mineral like ilmenite, rutile, zircon, monazite and sillimanite which are used in various fields of application like the paint industry, pharmaceuticals, nuclear sectors, communication, electronics, water purification, aviation, oil refineries etc. The exploration and exploitation of beach sand minerals started in the 20th Century, especially after the accidental discovery of monazite from the beach sands of Travancore state by a German scientist, Mr. Schomberry. The oldest mining in this area was for monazite. The deposit extends to a length of about 6 km, from the north of Muttom promontory to Colachel, with an average width of 45 m. The area north of Colachel to Midalam has been found to contain workable deposits of heavy minerals estimated to about 0.5 MT. The reserves of ilmenite and rutile are worked out to be around 0.31 MT and 15,300 tonnes respectively. The beaches at
Kanyakumari, Sanguthurai, Rajakkamangalam, Colachal and Inayam come under the non-mining beaches.

The beaches at Manakudi, Kadiapattinam, Manavalakurichi and Midalam are highly prone to erosion due to the above mining activities (Fig. 42). As the old beaches are dug for mining, the wave action on them increases, leading to strong swash and backwash that erode the beach to a few metres’ depth and form a cliff. Ultimately, a new beach at a lower height is formed, as noticed at Midalam (Fig. 43) and Inayam.
Stop 4: Teri Sands

One of the typical landforms in the area is a degraded sand dune topography of reddish brown hue, known collectively as coastal “Teri Sands”. Although the deposits occur in large patches roughly between Kanyakumari and Tuticorin, the topography is dominant along the coastal stretch between Kovalam and Manakudi, and in Muttam-Kadiyapattinam area (Fig. 44). The mean sand thickness increases from 1.5 m near the coastal headlands to 7.0 m inland, with weathered gravels and bedrock at depth. In Muttam area the dune topography is highly gullied. These reddish sands were deposited as a coastal dune system, mostly between 24 and 11 Ka, when the sea level was much lower (Jayangondaperumal, 2014). Subsequently it underwent rapid chemical weathering that led to kaolinite formation from the feldspar and concentration of hematite in the fine sediments that provided the reddish colour. Silica and carbonates precipitated within the sand profile, which favoured the localized formation of rhizoliths from the plant roots (Gardner, 1981; Hendry, 1987).

Fig. 44. Landscape on Teri sand dune deposits between Kovalam, Manakudi and Muttam.

Day 6:
Kanyakumari to Thiruvananthapuram
Depart from Thiruvananthapuram.
REFERENCES


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B8: Geomorphological Field Guide Book on THAR DESERT

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Fig. 1. Image-map of India, showing some places of interest for the 9th International Conference on Geomorphology, 2017 (Map prepared by A. Kar through processing of relevant ETM+ FCC mosaics and SRTM 1km DEM, both sourced from the US Geological Survey site). Boundaries are approximate.
### Geomorphological Field Guide Book on Thar Desert
*(12 November to 16 November, 2017)*

#### Itinerary

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Places from - to</th>
<th>Stay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>12 November 2017</td>
<td>New Delhi to Jodhpur by Flight; Field Visit to Sursagar, Osian, Central Arid Zone Research Institute (CAZRI) Research Farm at Jodhpur</td>
<td>Jodhpur</td>
</tr>
<tr>
<td>Day 2</td>
<td>13 November 2017</td>
<td>Jodhpur to Jaisalmer Field visit to Agolai, Balesar, Shetrawa, Dechu, Pokaran, Chandan</td>
<td>Jaisalmer</td>
</tr>
<tr>
<td>Day 3</td>
<td>14 November 2017</td>
<td>Jaisalmer to Sam and back Field visit to Damodara, Kuldhara, Kanoi, Sam</td>
<td>Jaisalmer</td>
</tr>
<tr>
<td>Day 4</td>
<td>15 November 2017</td>
<td>Jaisalmer to Jodhpur Field visit to Mokal, Bharamsar, Chhatrel, Rupsi, Lodurva</td>
<td>Jodhpur</td>
</tr>
<tr>
<td>Day 5</td>
<td>16 November 2017</td>
<td>Jodhpur to New Delhi by Flight</td>
<td>New Delhi</td>
</tr>
</tbody>
</table>
Notes
A. THAR DESERT: AN INTRODUCTION

Thar Desert, spread between the Aravalli Hill ranges in the east and the Indus River in the west, has its maximum area within India, and a smaller area in Pakistan. In India, the desert is spread over the western part of Rajasthan state, and forms a part of the hot arid zones of India that cover an area of 31.7 million hectare (m ha). While the arid western part of Rajasthan state (i.e., Thar Desert) covers an area of 19.6 m ha (61.9% of the total hot arid zone), there are other smaller hot arid areas, especially in the north-western part of Gujarat state (6.22 m ha, 19.6%), southern part of Punjab and Haryana states (2.75 m ha, 8.6%), south-western part of Andhra Pradesh state (6.8%), south-eastern part of Karnataka state (2.7%), and the north-central part of Maharashtra state (0.4%). India also possesses a cold arid zone that lies in the rugged Himalayan terrain within the state of Jammu and Kashmir (7 m ha).

The eastern limit of the arid western Rajasthan is along the calculated moisture availability index (also called the aridity index) of –66.6, which roughly passes through the foothill zone of the degraded, NNE to SSW-trending Aravalli hill ranges. From agricultural viewpoint, arid western Rajasthan can be divided into the following two agro-climatic regions: (a) the Western Dry Region, and (b) the Trans-Gangetic Plain Region, both having some sub-divisions (Fig. 2). Thar Desert lies essentially in the Western Dry Region, and has three subdivisions: (i) the arid western plain zone in the districts of Jaisalmer, Barmer, Bikaner, Churu and Jodhpur, covering 133074 sq. km, (ii) the transitional plain of inland drainage in Nagaur, Sikar and Jhunjhunun districts (31329 sq. km), and (iii) the transitional plain of Luni basin in Pali and Jalor districts (22951 sq. km). In the north, the Rajasthan irrigated north-western plain zone in the districts of Ganganagar and Hanumangarh (20557 sq. km), is largely a transitional plain between the Thar Desert and the arid Punjab-Haryana plains.
Climatic Characteristics

The key characteristic of arid regions is low precipitation compared to high atmospheric water demand. The hot arid region of India is no exception where annual rainfall is 100-500 mm and potential evapotranspiration (atmospheric water demand) is 1400-2000 mm (Goyal et al., 2013). Rainy season is quite distinct in Indian arid zone. The precipitation is mainly received during south-west monsoon season (June-September). The monsoon reaches the Thar Desert by 1st week July and the entire arid zone is covered by mid-July. The withdrawal of monsoon starts from the extreme west in Jaisalmer district by September. Thus, the monsoon season is effectively of 2.5 to 3 months, compared to four months in most parts of India. Only a few active monsoon spells bring rains in this region, resulting in wide inter- and intra-seasonal variations in rainfall amount. The annual rainfall in western Rajasthan, based on 1901-2010 rainfall data, is 291 mm, about 88% being received during the southwest monsoon season. High rainfall variability and coefficient of variation result in frequent droughts in this low-rainfall area (Rao and Roy, 2012). The rainfall deficit and duration of droughts vary from year to year and spatially. Early-season droughts due to late onset, terminal droughts due to early withdrawal and mid-season droughts due to breaks in monsoon are very common. Attri and Tyagi (2010) reported that west Rajasthan faced maximum (34) droughts during 1875-2009. At district or smaller scale, one or other pocket in arid zone faces drought almost every year as the temporal distribution of rainfall is also highly variable during the season. Floods are relatively less common, and are limited in area coverage because of light textured soils. However, flash floods sometimes do occur in small areas due to high intensity rains. There was increasing trend in annual as well as monsoon rainfall in west Rajasthan from 1901 to 2010. Presently there is a distinct rainfall gradient in western Rajasthan from east (500 mm) to west (150 mm). The mean annual rainfall in the districts within agro-climatic sub-zones of western Rajasthan are provided in Table 1.
Table 1. Mean annual rainfall in the districts of western Rajasthan

<table>
<thead>
<tr>
<th>District</th>
<th>Mean annual rainfall (mm)</th>
<th>Coefficient of variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arid Western Plain</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barmer</td>
<td>266.7</td>
<td>63</td>
</tr>
<tr>
<td>Jaisalmer</td>
<td>185.3</td>
<td>65</td>
</tr>
<tr>
<td>Bikaner</td>
<td>290.6</td>
<td>47</td>
</tr>
<tr>
<td>Jodhpur</td>
<td>368.9</td>
<td>52</td>
</tr>
<tr>
<td>Churu</td>
<td>365.7</td>
<td>37</td>
</tr>
<tr>
<td><strong>Canal Irrigated North Western Plain</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ganganagar</td>
<td>255.1</td>
<td>53</td>
</tr>
<tr>
<td>Hanumangar</td>
<td>250.5</td>
<td>56</td>
</tr>
<tr>
<td><strong>Transitional Plains of Inland Drainage Basin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sikar</td>
<td>467.4</td>
<td>42</td>
</tr>
<tr>
<td>Jhunjhunun</td>
<td>402.0</td>
<td>36</td>
</tr>
<tr>
<td>Nagaur</td>
<td>327.7</td>
<td>53</td>
</tr>
<tr>
<td><strong>Transitional Plains of Luni Drainage Basin</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pali</td>
<td>426.9</td>
<td>49</td>
</tr>
<tr>
<td>Jalor</td>
<td>381.0</td>
<td>52</td>
</tr>
</tbody>
</table>

Since cloud cover is low during most of the year, solar radiation is abundant. In arid Rajasthan, average annual solar radiation is about 22 MJ m\(^2\) per day. The value ranges from 15-18 MJ m\(^2\) per day in winter and 23-26.5 MJ m\(^2\) per day in summer (Rao and Roy, 2012). Solar radiation in drier districts of Jaisalmer and Barmer is higher (22.3 MJ m\(^2\) per day) than in the northern irrigated belt of Hanumangarh district (20 MJ m\(^2\) per day).

The diurnal, seasonal and annual temperature ranges are high owing to the geographical location, sandy terrain, sparse vegetation and low soil and atmospheric moisture content. During summer, the temperature may rise up to 50°C, while in winter -5.7°C has been recorded. During winter, the mean monthly maximum temperature ranges from 22°C to 29°C, and the mean minimum temperature ranges from 4°C to 14°C. May is the hottest month with mean maximum temperature of 40-42°C. The temperature declines by 3-5°C during monsoon season but again increases slightly during September and October when the monsoon withdraws.
The wind direction is normally southwest during summer and rainy season, and northeast during winter season. The wind speed remains quite low (3-4 km/h) during winter and high (9-12 km/h) during May to July. Strong winds of 15 to 18 km/h are often observed during June when the wind speed may reach 60 to 80 km/h during severe dust storms. Records for the last 40 years of the 20th Century suggest that the wind speed has declined gradually, particularly during the summer months (Kar, 2013). The decline was more pronounced up to the mid-1990s. A recent study (Vautard et al., 2010) found that winds are slowing in northern hemisphere. Such decline in wind speed was attributed mainly to changing patterns of atmospheric circulation, increased vegetation due to afforestation as well as changing landscape management practices and increase in urban density.

Geomorphology

Basement and the Late Quaternary Sedimentation
The Aravalli hill ranges, which form the eastern boundary of the desert over much of its length, were formed more than 2500 million years ago, and underwent at least three cycles of orogenesis and plantation since the Proterozoic. It is one of the oldest hill ranges in the world (Heron, 1953). The basement in much of the arid plain is made up of granite, rhyolite and the gneissic complex. From Upper Proterozoic period onward sedimentation here took place in several basins, under continental and marine conditions out of which the identified basins are: (i) Marwar basin, (ii) Lathi basin, (iii) Jaisalmer basin, (iv) Barmer basin, (v) Palana-Ganganagar Shelf, and (vi) Sanchor basin (Sinha Roy et al., 1998; Kar, 2011).

Studies based on morphological characteristics of landforms, stratigraphy and absolute dating of sediments have revealed that during the late Quaternary period climate oscillated in the region between dry and wet phases, and led to the relative dominance of fluvial and aeolian processes at different times (Ghose et al., 1977; Kar, 1995, 1999; Kar et al., 2004). Ghose et al. (1979) discovered a very old course of the Saraswati River from the Himalayas, buried under 40-60 m of dune sand in Jaisalmer district and adjoining parts of Cholistan Desert and in Tharparkar area of Pakistan through the dune-infested terrain of Kishangarh, Ghantiyal, Longewala, Shahgarh and Mondhlo. The discovery was made with the help of a set of the earliest, and coarse-resolution, Landsat imagery of the 1970s, aerial photo-interpretation and field survey in selected areas for geomorphological parameters. Kar and Ghose (1984), Kar (1999) revealed several other early courses of the Saraswati-Drishadvati river system from the Himalayas through the desert, and suggested that the thick alluvium in the dune-covered area between the Ghaggar River in the north and the
Luni River in the south was largely contributed by that system in pre-Holocene periods, with smaller contributions from the tributaries from the Aravallis and elsewhere.

Several phases of dune building activities have also been identified from within the desert and its eastern margin. In Ajmer-Pushkar area, two old phases of dune formation were found at the exposed base of old dunes, which were topped by a layer of modern sand (Goudie et al., 1973; Allchin et al., 1978). Recent studies have identified several other dune building phases within the desert and its margin, dating back to more than 100 ka (kilo annum) before present (Kar et al., 2001).

A multi-disciplinary and multi-institutional study on the aeolian stratigraphy in the desert and its margins revealed that the history of aeolian sedimentation dates back to at least 150 ka. Several aeolian episodes have been dated to around 100-115 ka, 65-75 ka, ~55 ka, 30-25 ka (Kar et al., 2004; Singhvi and Kar, 2004). Wetter phases in between in the east and south resulted in partial leaching of carbonates from the profiles. During the last 20 ka the principal periods of sand accumulation were 14-7 ka, 5-3 ka and around 2 ka. Most of the major sand dunes show a strong phase of aeolian accumulation during the terminal Pleistocene. This was a period when SW monsoon wind started building up. The beginning of Holocene was marked by increased rainfall that peaked around 6 ka and resulted in large scale landscape stabilization. The present rate of century-scale sand mobility is much higher than the past geological rates (Kar et al., 1998, 2001; Thomas et al., 1999). Summary of research is available in (Kar et al., 2004; Singhvi and Kar, 2004).

**Present Landforms**

Broadly, the landforms in Thar Desert are fluvial, aeolian and lacustrine. The efficiency of aeolian processes now increases with decreasing rainfall from east to west, as well as with the increasing wind speed in that direction (Kar, 1993a). The Luni River forms the only organised drainage system. Surface water resources are limited due to low and scanty rainfall and poor water-yielding efficiency of sandy terrain. Besides storage tanks, other common systems for surface water are Nadis (village ponds) and Khadins (runoff harvesting systems). Vegetation constitutes to be primary source of life support because of dependency by animal husbandry. The northern desert thorn forest, northern Acacia scrub forest, northern Euphorbia scrub and inland dune scrub are the recognised forest types in this region.

A very small area in the south comes under fluvio-marine processes, where the northern fringe of Great Rann of Kachchh is a part of the mapped area. Kar (1993a) recognised nine major dune types and twenty-three subtypes in Thar Desert, which
can be grouped under the old dune system and the new dune system (Pandey et al., 1964; Vats et al., 1976; Singh, 1982).

Geomorphological Mapping
During 2012-2015, under a National Level Mapping project of ISRO’s (Indian Space Research Organization) NRC (Natural Resources Census) programme and with technical collaboration of GSI (Geological Survey of India, Western Region), CAZRI prepared a geomorphological map of arid western Rajasthan at 1:50,000 scale, using a recently developed classification system. The mapping involved digital interpretation of the false colour composite (FCC) of images of 2005-06 from Indian Remote Sensing Satellite (IRS), LISS-III, followed by field verification of the mapped units and analysis of sediments. The mapping (Fig. 3) shows that aeolian landforms are most dominant in the area (~79% of the total area), but actual area covered by sand dunes is about 48%. Based on the origin, six types of landforms have been identified: structural, denudational, fluvial, aeolian, fluvio-marine and anthropogenic (Moharana et al., 2013). A brief description of the result is presented below.

Major Landforms
Landforms of structural origin account for only 2.4% area of western Rajasthan, while those of denudational origin occupy 5.1% area. The major forms are hills and valleys, dykes and ridges, pediments and pediplains. However there is marked variations in morphology and origin. In Jaisalmer district, the hills are low and scattered distributed; in contrast, Barmer and Jalor districts have few clusters of inselbergs and domes. Hamadas, the rocky structural plains, occur in Jaisalmer district. Isolated sandstone hills in Jodhpur and Nagaur districts occur as mesas and buttes while those occurring at Agolai, Korna, Gotan, Pundlu, Bilara are of rhyolite and limestone hills.
Fluvial landforms:
The major fluvial landform sequence follows hills and uplands, rocky/gravelly pediments/pavements, buried pediments, flat older alluvial plains, younger alluvial plains and riverbeds.

Desert pavements, covering 3.3% area, occur mainly along a discontinuous belt from Shiv to Bikaner through Sankra, Bhojka, Bap and Kolayat in the districts of Barmer, Jaisalmer, Jodhpur and Bikaner. Other notable occurrences are between Phalodi and Bap in Jodhpur in a continuous belt at Shekhasar, Ramdevra and Damodara till Sam in Jaisalmer (Moharana and Raja, 2016). The pavement surfaces are strewn with gravels and pebbles in a matrix of sand, silt and clay, which were interpreted by Bakliwal and Grover (1988) as remnants of the Saraswati palaeochannels. The pavements have a broadly convex outline, with rills and gullies along their margins. Kar (1995, 2014) explained the gravel spread as weathering and erosion of a conglomeratic bed of Jurassic age.

Older alluvial plains are usually characterised by layers of fluvial and aeolian sediments and by zones of illuviated soft nodular carbonates (kankar) or gypsum at 30-300 cm depth within the alluvium (Ghose, 1964; Ghose et al., 1977). Younger alluvial plains cover only 2.1% area of western Rajasthan, but have very high relevance for agricultural uses, as these are well endowed with shallow groundwater. The plains occur in narrow zones along the 462.5 km long Luni River and its major tributaries like the Jawai, the Lilri, the Guhiya, the Sukri, the Bandi, the Mithri, the Khari and the Sagi. A small strip is also noticed along the Kantli River in Jhunjhunun district. All these streams originate from the Aravalli hill ranges, are ephemeral and flow only during the monsoon season. Because of the meagre and uncertain rainfall, water flows along the full length of the channels only during high-rainfall years, and that too for a few hours to days. The thick sandy plains, in which the channels have been formed, absorb much of the water during each flow, while the sandy banks encourage more widening of the beds than deepening. The stream beds exhibit an alternate sequence of erosional features and depositional lobes all along their courses. Even the small upland channels exhibit such alternate sequence of scour and fill (Moharana and Kar, 2010). Water from many of the small channels is impounded by the villagers in Nadis (ponds) and Khadins (runoff farming system) for humans and livestock consumption and even for farming activities (in Khadins). The flow path of the channels often gets obliterated in thick sand. Moharana and Kar (2002) simulated the development of drainage network in a gravely and sandy terrain of the desert from available topographic height information, which can help in finding the better sites for runoff conservation.
A small delta of the Luni River has been mapped downstream of Gandap, which is south of the river’s confluence with the Jawai River. The delta is about 20 km wide, in which the Luni bifurcates into several streamlets before meeting the Great Rann of Kachchh. Although the delta formation is now almost defunct, the deep alluvium between Gandap and the margin of the Great Rann of Kachchh suggests that the delta-building process was active during some previous wetter climatic phases. The western margin of the delta appears to be gradually covered under aeolian sand.

**Aeolian landforms:**
The aeolian landforms are dominated by sand dunes of various types and morphology, further categorised and mapped as barchan, longitudinal, transverse, parabolic, dune complex and dissected dune complex (where the dune slope has numerous gullies). Sand dunes occur in about 48% area of the region. There are several studies on the occurrence, pattern and types of sand dunes. Kar (1993a) identified and mapped nine major and 21 subgroups of sand dunes in western Rajasthan. Moharana et al. (2013) delineated barchan, longitudinal, transverse, parabolic, dune complex (in areas where the form is a result of complex wind pattern) and dissected dune complex (where the dune slope has numerous gullies) (Fig. 4) at 1:50,000 scale. Barchans occur mostly to the west and south-west of Jaisalmer, especially between Shahgarh and Dhanana, where they are mostly 15 to 40 m high, coalesced, and occur in long chains within the longitudinal dune field. Kar (1987, 1990a) classified these dunes as megabarchanoids, and explained their formation mechanism. Small barchans (1-5 m high) occur in many parts of the desert, but beyond the western part of Jaisalmer and Barmer districts these seldom occur in clusters. The longitudinal dunes occur dominantly to the west and south-west of Jaisalmer, where Kar (1987) identified small feathers along the flank of these dunes and inverted Y junctions. Smaller occurrences have been mapped
notably near Bikaner, Didwana and Lachhmangarh. The orientation of the dune gradually changes from WSW in the westernmost part to SW in the eastern part. Kar (1987, 1993a) discussed different modes of formation of the linear sand dunes, including formation from streams of barchans and due to vortices along hill margins, etc. Transverse dunes have been mapped mainly to the west of Bikaner, NW of Jaisalmer, and in parts of Ganganagar and Hanumangarh districts. The dunes generally occur in 1-5 km long chains with narrow interdune plains in between. In Bikampur-Karanpur area the dunes are 20-40 m high, but those in the east are mostly 8-15 m high. Parabolic dunes with two arms in the upwind direction and a curved nose downwind, constitute the major dune type in Thar Desert. Their major occurrences are in Barmer, Jaisalmer, Jodhpur and Bikaner districts. The dunes usually occur in chains of 4 to 8, or more. In the west, their arms are 5-8 km long, which gradually shorten eastward to about 1 km or less (Kar, 1993a). Dune complex, consisting of several dune types, have been mapped in the northern part of the desert, mainly in Churu district in extreme temperature situation. These dunes are 12 m to 20 m high with narrow interdune plains. Dissected dune complex, which usually include the major obstacle dunes along the hill slopes and some parabolic and other dunes along the wetter eastern margin of the desert, are numerous along the foothills of the Aravalli hills, the Siwana hills and the isolated hills in the sand-covered areas. The runoff from the rocky slopes run through the dunes, forming rills and gullies. The mappable interdune plains cover 8.2% area, and are mostly flat sandy or sandy undulating. The major occurrences have been mapped in Barmer, Jaisalmer, Bikaner, Churu, Ganganagar and Hanumangarh districts.

Playas or the inland Ranns:
Playas or saline depressions (also called the inland Ranns) occur throughout the region. The notable playas in the dominantly sandy terrain are Sambhar, Didwana, Tal Chhapar, Pachpadra, Thob, Bap and Lunkaransar, while those in rocky terrain are Lawan, Pokaran, Dediya, Mitha Rann, Kanodwala Rann and Kharariwala Rann. The Sambhar Lake along the eastern margin of the desert is the largest, followed by those at Bap and Pachpadra. Most playa surfaces remain dry almost throughout the year, and get flooded during the monsoon period when a centripetal drainage system brings water and sediments from the surrounding catchment areas. The sediment profile consists of alternate layers of silt, clay and sand, as well as gypsum at places (Singh et al., 1974; Deotare et al. 2004). Aggarwal (1957) first postulated a riverine connection for the Pachpadra and Didwana lakes, while Ghose (1964) suggested that salt deposition took place at the confluence of streams, especially at Pachpadra and Thob. Kar (1990b, 1993b) suggested that a process of deflation in the wake of high hills, dune formation along the hill margins and trapping of ephemeral channels in the deflation hollows led to the formation of many playas in eastern Thar. Kar (1993b,
2011) also suggested that a long-continued process of sand blasting on softer limestone beds formed the playa basins in Jaisalmer-Mohangarh area, while neotectonism might have played a major role in the formation of Sambhar Lake and some small playas in the Luni basin.

**Anthropogenic landforms:**

Landforms of anthropogenic origin are manifestations of the impact of human activities. Levelling of sand dunes through mechanical methods for cropping has enlarged the area under the plains, mainly in the northern part. Mining of salts and chemicals in salt pans in 118 km² area, and mining of sandstone, limestone, marble, gypsum, clays and lignite in 176 km² area, have not only altered the local drainage system in some areas, but have also created large depressions.

**Land Degradation in Western Rajasthan**

Several studies carried out during the last five decades in western Rajasthan have revealed that the major types of land degradation in the area are wind erosion, water erosion and land salinization. Among these, wind erosion is the most important and widespread. Because of the meagre rainfall, water erosion is localized, and occurs mainly in the eastern part. Salinity/alkalinity of land is partly related to natural causes, but also due to faulty and excess use of water for irrigation. In recent times, water pollution due to industrial effluents and mining activities has also become a major cause of land degradation. Thus, land use has been found to have an important effect on degradation, especially as expansion and intensification of agriculture, overuse of the natural vegetation resources and industry-related activities have led to not only degradation of rangelands and forests, but have also aided wind and water erosion processes and salinity build-up. Results of research on some of the processes are summarised below, followed by a short description of the mapping.

**Wind erosivity measurement:**

Aeolian activities in the Thar are mostly restricted to summer months as impacts of hot wind blowing from SSW and SW. The NE wind during winter is weak and poor agent for shifting of dunes. The wind strength shows a gradual decline from west to east and the precipitation effectiveness (PE) improves in that direction. Kar (1993a, 1994b) calculated erosion potential of the wind or the erosivity in the form of wind erosion index (WEI) for several meteorological stations of the desert. The annual WEI value was calculated as the sum of the values from March to July. The index values ranged from very low (Index 1-14) to extreme high (index value 480 and above). The analysis and mapping showed that maximum potential wind erosion lies to the SW of Jaisalmer and in adjoining parts of Pakistan, while the lower values occur towards east and north east. WEI calculations for 21st Century on the basis of data from different GCM simulations showed a progressive rise with time (Kar, 2012).
Wind erosion measurements:
Scientists at Central Arid Zone Research Institute carried out studies on the aspects of wind erosion mainly focusing on, (1) satellite based mapping of wind erosion and related desertification in western Rajasthan, (2) field measurements of wind erosion. Mapping based on visual interpretation of the 1:250000 scale FCC of Landsat TM images and ground truth revealed that about 76% area of western Rajasthan was affected by wind erosion (Narain et al., 2000). While 15% area was severe to very severely affected, 36% area was moderately affected and 25% slightly (Fig. 5).

Ramakrishna et al. (1990) measured during a gusty wind the sand transport on a dune crest at Shergarh, situated 100 km away from Jodhpur, as 46 kg/m2/hour. Kar (1994b, 2013) measured the movement of few barchans near Pokaran for 5 years and found a mean mobility rate of 32 m per year. Gupta (1993) found soil loss from a sandy soil much higher than from a loamy sand soil and that clod formation and vegetation were also important factors. At wind speed of 20 km/h the grass cover on a sandy soil at Chandan near Jaisalmer reduced erosion to 76.7 kg/ha/day, while a bare sandy soil at Bikaner lost 273.7 kg/ha/day. Effects of tillage, presence of crop stubbles are also important influencing factors in wind erosion. Excessive tillage before the kharif was found to lower the percentage of clods and thus increase the rates of wind erosion. Measurement during a sandstorm at Bikaner showed more erosion from a bare sandy soil plot (1449 t/ha) than a crop field nearby with a cover of 45 cm high pearl millet stubble (22 t/ha). Fields deep ploughed using tractors lost heavily (mean loss of 2837 t/ha) than soils under 8-12 per cent cover of natural vegetation (472 t/ha; Dhir et al., 1992). Using a CAZRI-developed sand sampler,
Santra et al. (2010) reported soil loss during a sand storm in 2004 as 827 kg/ha from an overgrazed site at Jaisalmer and 240 kg/ha from a controlled grazing site at Chandan. They also showed how aeolian mass flux got reduced with height above the surface. Soni et al. (2013) used erosion pins to measure sand loss from different crop fields at Bikaner.

**Fluvial process measurements:**
CAZRI carried out a detailed field-based measurement of water erosion in a small upland stream catchment on a hill-rocky/gravelly pediment - colluvial plain sequence at Agolai near Jodhpur (9.3 ha, second order ephemeral channel, 1.0 - 1.4 km long and 1.0 - 1.5 m deep), which involved repeated measurement at fixed locations to record channel configuration, water and sediment flow, and other parameters during and after a rainfall event for a number of years. A rough estimate of velocity was made by measuring the time required for a float to travel a fixed distance along the stream at selected cross-sections. To monitor bed load movement along the main channel, key particles >2 mm size were coloured and placed at different locations of the channel. All the particles were grouped under weight groups of >100 g, 51-100 g, and <51 g. For understanding aspects of shape factor and sediment movement, the degree of flattening (flatness index) of each particle was calculated and was measured under three categories: <25, 26-50 and >50. During 2007, two high rainfall events of 42 mm and 52 mm generated measurable runoffs with peak discharge of 20 m3/s (upstream) and 13 m3/s (downstream). These moved the bedload sediments to distances of 43-141 m in the upstream, 6-28 m in the middle reach and 63-95 m in the lower reach. The long and cross profile measurements showed a sequence of alternate deposition and erosion throughout the channel with a marked asymmetry in the form of concavity (scours) and convexity (fills) in the lower reach. Cross profile measurement showed bank cuts (6 cm) and vertical incision (1-2 cm) on the rocky-gravelly V shaped valley in the upper reach, incision (4-30 cm) and localized higher deposition (10-12 cm) in the narrow (<1 m) and deep (1.5 m) U shaped valleys in the middle reach and mainly deposition (13 cm) on the wide (1-4 m) and shallow channels (0.1 to 0.2 m) in the lower reach. The rain storms showed more impact on the bed load movement. Analysis of particle weight and distance moved by them indicated, 62.5% particles in the upper reach (av. wt = 214 g), 87% in the middle reach (av. wt = 129.7 g) and 26.4% in the lower reach (av. wt = 83.1 g) moved less than 50 m distance. Among the lighter weight group (<50 g) the highest (124.56 m) and the lowest displacement (28.80 m) were recorded at upper and middle reaches, while the maximum displacement (60-70m) of heavier particles (>100 g) occurred in the lower reaches. Similarly, less flat particles (FI 0-25), moved maximum in the lower section and minimum in the middle section. The more flat particles (FI >50) moved maximum distances in the upper reach. In general it was found that particles <50g weight and less flat (FI = <25) experienced the highest displacement (95-106 m).
These spatio-temporal bed load movements presented a view of cascading flow as generally is noticed during desert floods (Moharana and Kar, 2010).

**Simulation of a revived drainage system after flood:**
Several major floods have occurred in the region during the last four decades, the most notable ones taking place during 1975, 1979, 1983, 1990 and 2006. The high rainfall event in 1979 in parts of Jodhpur, Pali and Jalor districts led to very high flood-related damages in the central part of Luni basin. The floods of 1975 and 1990 were more widespread in the Luni basin area, causing large flow along all the streams and revival of some palaeochannels (Kar, 1994a). Another widespread flood-causing rainfall event in the southern part of the desert took place in 2006 when a partially buried drainage system of the Rohilli River in Barmer district got rejuvenated after about 8 decades, and created havoc in Shiv-Kawas area (Kar et al., 2007). During that event from 17th to 24th August, several stations in the northern part of Barmer district and adjoining part of Jaisalmer district were inundated because of 300-400 mm rainfall (*Fig. 6*). The catchment areas have a number of dry streams that are partly covered by low sand dunes. It was found that in the flow path of the flood water in the upstream areas, there were many water conservation structures which breached almost simultaneously under the high intensity rainfall, resulting in a huge surge of water through the dry channels. Some abandoned channels were also revived. A GIS and remote sensing based channel simulation of the area revealed the partial revival of a major right-bank tributary of the Luni River (Kar et al., 2007b). Earlier it was believed that the Lik River, originating near Pokaran in Jaisalmer was the westernmost right-bank tributary of the Luni, but the 2006 flood revealed a longer right-bank tributary from near Mehreri in Jaisalmer district that carried the waters of Rohilli River catchment from Shiv-Kotara area and other streams from the Baisala hills catchment and the Luni hills catchment, to Kawas and beyond. Beyond Kawas, the stream possibly used to meet the Luni to the south of Sindri, but got subsequently dismembered by high sand dunes. The sediments washed down from uplands...
contained micaceous clay having 8-15 times higher N (880-3234 kg ha\(^{-1}\)), 3-4 times higher P (20-55 kg ha\(^{-1}\)) and 2-9 times higher K (270-1249 kg ha\(^{-1}\)) than in the underlying soils, making the land much fertile than before (Kar et al., 2007b). Thus, the study indicated that even in a desert, the old and the abandoned stream courses are potential sites for disaster if their passage is obstructed.

**Desertification mapping:**

Based largely on field- and aerial photo-based mapping, CAZRI first prepared a desertification map of western Rajasthan in 1977 for the UN Conference on Desertification at Nairobi. In the early 1990’s, CAZRI carried out a satellite-based mapping at 1:1 M scale, for which 1:250,000 scale FCCs of Landsat-TM images for 1989-1991 were visually interpreted. According to the above mapping, out of 20.875 m ha area mapped, 19.175 m ha (92% of the total mapped area) was degraded, and the rest was free from any degradation. While 33% area was slightly affected, 35% area was moderately affected and 24% severely. Wind erosion constituted the largest area (~76% of the total mapped; 25% slightly affected, 35% moderately and 15% severely). Water erosion was mapped in 15% area, while waterlogging and salinity was mapped in 6% area. The institute then suggested a set of field indicators that helped researchers to interpret the levels of land degradation due to wind erosion and other forms of degradation (Singh et al., 1992).

In 2007 CAZRI prepared a desertification status map (DSM) for arid Rajasthan and Gujarat at 1:1 M scale, which formed a part of the country’s map on land degradation for the Thematic Programme Network-1(TPN-1) of UN Convention to Combat Desertification (Fig. 7). The mapping revealed that ~76% area of western Rajasthan was affected by wind erosion, encompassing all the major land uses, but mostly under croplands and dunes/sandy areas, while water erosion affected ~2% (mostly in croplands and scrublands), salinization ~2% (mostly in croplands) and vegetation degradation ~3% (especially in scrublands and forests). Mining activities had spoiled only 0.10% area, and degraded rocky areas covered 1% area. About 18% area was severely degraded and 66% slight to moderately, while 16% area is not affected by degradation (Kar et al., 2007a). This national mapping was coordinated by the Space Applications Centre (SAC) of the Indian Space Research Organisation (ISRO), and used a 3-tier classification system for interpreting the images of 2003 to 2004 from AWiFS sensor on board India’s IRS-P6 satellite (SAC, 2007). A review of the above desertification researches, including control methods adopted by CAZRI, is provided in Kar et al. (2009).

In 2013-16 CAZRI participated in the DSM Cycle-II project of SAC to map the degradation in Rajasthan state from satellite data for 2011-13, and to find the changes from the earlier mapping with satellite data of 2003-05. The map for 2011-
indicated that as per 2011-13 data, 62.90% area of the total geographical area of Rajasthan (34223900 ha) was affected by various process of desertification (Fig. 8). This indicated an overall decrease of degraded area by 99092 ha (from 21625604 ha or 63.13% in 2003-05 to 21526512 ha or 62.90% in 2011-13). Area affected by wind erosion / deposition covered the maximum area: 15332053 ha (44.80%) in 2003-05 and 15197873 ha (44.41%) in 2011-13, indicating a decrease by 0.39% area. Water erosion affected about 2116315 ha (6.97%) in 2011-13 data, indicating an increase by 0.8% area in comparison to 2003-05. Vegetation degradation was assessed in 2606222 ha (7.61% area) in 2011-13, an increase by 0.03% area over 2003-05. Area under salinity/alkalinity decreased by 1898 ha (Moharana et al., 2016).
Socio-economic Conditions

Despite the limitations of an arid environment, Thar Desert in western Rajasthan has a high population density for any desert. According to the 2011 census, human population is 28.15 million, and may reach 41 million by 2031. In case of livestock, the 2012 census shows a total of 30.18 millions (20.5% cattle, 13.0% buffalo, 22.8% sheep, 42.4% goat, 0.9% camel). Both the human and the livestock population are showing an increasing trend in the region. Between 1961 and 2011 census, human population in western Rajasthan has increased by >250%, while between 1956 and 2012 census, the animal population has increased by about 125%. Cattle population has increased by 57.7%, while sheep and goat populations have increased by 44.8% and 26.6%, respectively. The most spectacular increase has, however, been in case of buffalo, which has increased by 412.5%, especially in the irrigated areas. The patterns of human population in different districts of Rajasthan state during 1991, 2001 and 2011 census are shown in (Fig. 9).

![Fig. 9](image)

*Fig. 9*

*District-level population in Rajasthan state.*
Irrespective of frequent droughts, the region has a dominant agricultural economy. The land use mapping by CAZRI for 2005-06 shows 61.15% area of western Rajasthan under cultivation, which includes 51.19% as net sown area, 9.96% as double cropped area and 12.97% as net irrigated area. Wastelands were mapped in 29.4% area (Fig. 10). When compared with an earlier land use map by CAZRI, prepared in 1982-83, an increase in net irrigated area by 128%, and in double cropped area by 70% is noticed, whereas a decline of culturable waste area by 7.70% took place. An analysis of production and income for the period 2007-08 showed that in the four agro-climatic zones of western Rajasthan, income from agricultural sector contributed 26-43% of the total income, the mining 1.6-1.8%, and other sectors like service, business and allied activities contributed 56-73% of the total income (CAZRI Vision 2030). In agricultural sector, income from cropping provided 59-71% of the total agricultural income, while livestock provided 28-42%.

Net sown area in western Rajasthan is showing an increasing trend, mainly at the cost of fallow lands. According to the land use statistics for 2010-11 the net sown area in western Rajasthan was 56.8%, current fallow 4.7% and other fallow lands 5.8%. Forests occupied 3%, pasture 4%, land put to non-agricultural use 5%, and barren uncultivable land 4.8%. The net irrigated area is 13% of the total geographical area.
Pearl millet, grown during the summer monsoon (Kharif season) in about 4.2 million ha (m ha) area, is the major food crop in western Rajasthan, and a staple food of the inhabitants, especially in the rural areas. The region produces 25% of the country’s total pearl millet production. Cluster bean, Moth bean, Cowpea and Horse gram are the other major crops grown during the Kharif season. Area under cluster bean is about 2.8 m ha. Moth bean is cultivated in about 1.6 m ha. Sesame, groundnut, castor are also grown in significant area. Since rainfall is highly erratic and drought occurs frequently, Kharif crop production has high inter-annual variation. CAZRI and few agricultural universities have developed several drought-resistant and early-growing crop varieties that help to improve the crop production. Cotton is grown mainly in the northern part. During winter several irrigated crops are grown, which include wheat, mustard, some pulses, chilli and several spices and medicinal plants like coriander, cumin, garlic, isabgol, fennel and fenugreek. These winter crops are essentially the cash crops, and provide good income to the farmers. Gram is also grown, but mostly in conserved moisture.

Important horticulture crops of the region are Ber (Ziziphus mauritiana), pomegranate, Aonla (Emblica officinalis) and Bael (Aegle marmelos). Date palm is also grown with some success. Medicinal plants like Aloe vera, Sonamukhi are also grown. Areas surrounding the major towns and cities grow vegetables in limited areas. Broadly, the region has now surplus production of cereals and pulses but production of oilseeds, fruits and vegetables still lag behind. The overall progress of agriculture is the result of improvement in agro-technologies, infrastructure development and irrigation water availability in the form of groundwater wells, IGNP Canal and Narmada Canal. However, few problems of waterlogging and soil salinity due to faulty irrigation need proper management.

The omission of reference to Fig. 11 on text pages was my mistake. Fig. 11 is already available with you. The image and caption below are for your ready reference. Kindly adjust as suggested above.

Fig. 11.
Monthly rainfall at Jodhpur in 2010.
Day 1: 12/11/2017
New Delhi to Jodhpur by Flight
Visit to CAZRI and Mehrangarh Fort
Stay at Jodhpur.

The first day of the visit will be spent on visiting the office and research facilities of Central Arid Zone Research Institute (CAZRI) Institute at Jodhpur, followed by a visit to Mehrangarh Fort to have a bird’s eye view of Jodhpur city and the terrain around it. Jodhpur, popularly known as the “Sun City”, is the second largest city in Rajasthan, having a population of 1.14 million (2011 census). Being located in the desert proper the city experiences extremes of weather. The peak summer temperature during May often crosses 47°C, the mean maximum being 41.2°C, but the highest recorded so far is 48.9°C. The minimum temperature is recorded in January, when the mean minimum value is 9.6°C, while the lowest recorded is -2.2°C. The mean annual rainfall in the city is 359 mm, received 20 days, but with a coefficient of variation of 46%. The highest rainfall received in any year was 815 mm, while the minimum received was 91 mm. About 90% of the annual total is received during the summer monsoon months of June to September (Fig. 11). The highest one-day rainfall received was 157 mm on 31 July 1990.

Stop 1: CAZRI Research Facilities and Farm at Jodhpur
The headquarters of Central Arid Zone Research Institute (CAZRI) is located in the southern part of the Jodhpur city, where it has its main research farm and experimental laboratories. The Institute had a humble beginning in 1952 as a Desert Afforestation Research Station. In the early 1950s there was strong apprehension among the academicians and policy makers in India that the Thar Desert was spreading towards the wetter east at an alarming rate, and that it might engulf large fertile areas of present day Punjab, Haryana, Delhi, western part of Utter Pradesh and the eastern part of Rajasthan. The climate of the period was marked by low rainfall, high wind speed and high frequency of droughts. The Government of India, therefore, established a Desert Afforestation Research Station at Jodhpur in 1952, mainly to focus on sand dune stabilization and shelterbelt plantations, so as to check wind erosion. In 1957, the Station was reorganized as Desert Afforestation and Soil Conservation Station. On October 1, 1959 Government of India, on the advice of Dr. C.S. Christian, a UNESCO expert from CSIRO, Australia, reorganized the Station into a major centre for arid zone research, called the Central Arid Zone Research Institute. While proposing the Institute, the guiding principles were spelt out as study of fundamental aspects of the problems and development of principles of control.
measures. More focus was laid on a holistic approach that recognizes the fragility of the arid landscape and strength of the region in mixed agriculture, consisting of both crops and livestock. In other words, the Institute was created for research addressing the environmental and livelihood-based issues of the region, with emphasis on conservation agriculture. This was one of the first International Institutes of its kind funded by UNESCO under its programme of International Studies on Arid Zones. On April 1, 1966 CAZRI was brought under the administrative control of Indian Council of Agricultural Research (Fig. 12).

At present, CAZRI has five Regional Research Stations (RRSs) at Bikaner, Jaisalmer and Pali in Rajasthan, at Kukma-Bhuj in Gujarat and at Leh in Jammu and Kashmir. The RRS at Leh was established in August, 2012 to address the agricultural problems of cold arid region. CAZRI also has three agricultural technology centres, or the Krishi Vigyan Kendras (KVKs), located at Jodhpur, Pali and Kukma-Bhuj. The institute also manages five experimental field areas for range management studies, and hosts an All India Network Project on Vertebrate Pest Management that has many sub-centres in agricultural institutes and universities across the country. At present the mandates of the institute are: (a) basic and applied research on sustainable farming systems in the arid ecosystem, (b) repository of information on the state of natural resources and desertification processes, (c) livestock-based farming systems and range management practices for the chronically drought-affected areas, and (d) generating and transferring location-specific technologies.
Since its inception, CAZRI has been following an integrated resources management approach. It has carried out landmark research on subjects like: assessment, monitoring and management of natural resources of the Indian arid zone; development of integrated farming systems; improvement of crops, grasses, shrubs, trees and fruits; livestock production and management; use of alternate energy resources, etc. The institute has evolved strategies for combating drought and desertification. It has developed several need-based and cost-effective technologies like shelterbelt plantation, wind erosion control, sand dune stabilization, watershed development, rehabilitation of wastelands, arid land farming systems, alternate land use strategies, range management, pest management, post-harvest technologies and value addition of crops and livestock products, development of farm implements useful for the dry sandy terrain, etc. Several solar energy devices like solar cooker, solar water heater, animal feed solar cooker, solar dryers, solar candle making device, PV duster, PV winnower, PV based water pumping system for irrigation, etc., have also been developed. CAZRI’s improved varieties of Ber (Fig. 13) provides the desert farmers a cost-effective means to combat severe droughts when most crops fail to survive, as the plant requires less water than the crop plants and need less maintenance, while the farmers can reap the harvest of its nutritious fruits, fodder from its leaves and fuel wood from its branches. These and other horticultural products have become very popular in India and abroad (Fig. 14). Its pearl millet varieties have also proved to be wonder crops as these can withstand early and mid-season droughts, and are quick-growing with adequate grain and fodder

Fig. 13.
An improved variety of Ber during the fruiting season.

Fig. 14.
A demonstration of some fruits developed by CAZRI.

Fig. 15.
CZP 9806, an improved variety of pearl millet from CAZRI.
production (Fig. 15). CAZRI’s aloe-based research has produced some popular health and food products. Many of the silvo-pastoral, agronomic, horticultural and other plant-based experiments, with emphasis on dryland farming technologies, are conducted at the institute’s Research Farm at Jodhpur. Farmers and other stakeholders from the region are invited regularly to demonstration of results during the cropping season, when they are also guided about the methodologies, post-harvest technologies, etc. The institute remains in direct contact with the farmers through its extension wing and three KVKs. An Agricultural Technology Information Centre (ATIC) caters to the needs of the farming community and others interested in the technologies and produce of CAZRI. The institute also works in close liaison with several national and international institutes and stakeholders working for the development of arid agro-ecosystem. CAZRI takes pride in developing since inception 52 research areas for silvopasture, where it conducted elaborate grazing studies and demonstrated the benefits of range management, as also the methodologies for sand dune stabilization, shelterbelt plantation, etc. After developing the research areas CAZRI handed them over to the Government of Rajasthan, except the five experimental areas mentioned above.

Stop 2: Mehrangarh Fort
Mehrangarh Fort is one of the tallest and imposing forts in India (Fig. 16). Built in 1460 by Rao Jodha on a rhyolite hillock, the fort is situated 410 feet (125 m) above the city and is enclosed by imposing thick walls. Inside the fort there are several palatial buildings known for their intricate carvings and expansive courtyards. A winding road leads to and from the city below. There are seven gates of the fort, which include Jay Pol (meaning victory gate), built by Maharaja Man Singh to commemorate his victories over Jaipur and Bikaner armies, and Fateh Pol (also meaning victory gate), which was built by Maharaja Ajit Singh to mark the defeat of the Mughals. The palm imprints on these gates still receive much tourist attention. The fort was constructed when the ancient palace at Mandore, the capital of Marwar State for a long time, was to be shifted due to frequent attacks by
the enemies. Mandore is located about 7 km to the north of the fort, and is now a tourist destination for its beautiful garden, and the cenotaphs erected in memory of the several kings of Marwar.

The museum in the Mehrangarh fort is one of the well-stocked museums in Rajasthan. In one section of the museum there is a selection of old royal palanquins, including the elaborate domed gilt Mahadol palanquin, which was won in a battle from the Governor of Gujarat in 1730. The museum exhibits the rich heritage of the then-ruling Rathore clan in the form of arms, costumes, paintings and decorated rooms.

**Day 2: 13/11/2017**

**Jodhpur to Agolai, Balesar, Shetrawa, Dechu, Pokaran, Chandan and Jaisalmer**

Stay at Jaisalmer.

Jaisalmer is located about 300 km west of Jodhpur, and the route is through a variety of sandy and rocky-gravelly terrain, with spectacular views of the parabolic sand dunes, the playas, the pediments and pavements, as well as sandy undulating plains. The rainfall decreases gradually westward from Jodhpur. Balesar, at a distance of about 65 km from Jodhpur receives an annual rainfall of ~285 mm, while Pokaran, about 165 km from Jodhpur receives 203 mm, and Jaisalmer, 300 km west of Jodhpur, receives 195 mm. Further west, Sam, about 50 km from Jaisalmer, receives 180 mm. As the rainfall decreases, so does the rainy days. This change is reflected in a gradual decline in plant cover westward, as well as an increase in aeolian features. Topographically, we shall move towards a lower elevation which varies from about 230 m at Jodhpur to 225 m at Jaisalmer.

Landforms will be both rocky and sandy, with a distinct nodular carbonate horizon at some depth. Radiocarbon dating of the CaCo3 nodules near Jodhpur has suggested its formation between 40k and 20k BP. This phase was followed by a major dry phase when much of the present day dunes were formed. Another major wet phase arrived during 10k to 3.8k B.P which prevailed upon to stabilize the bigger dunes. So terrain at Jodhpur will have low hillocks (ryolite and sandstone), followed by low denuded rhyolite hillocks at Agolai, sandstone (rocky uplands) and sand dunes at Balesar (sandstone mining area), Shetrawa, Dechu. The saline depressions will appear amidst the sandy terrain at Khara Bhagotiya, Lawan and Pokaran. From here, the terrain will be almost flat and some extensive desert pavements will be the major feature. It will be a different rocky/gravelly pavement surface between Chandan and Jaisalmer where tone will see occurrence of rounded and surrounded gravels. This may suggest a marine connection to this region in the distant past. Intermixed with rocky plains, there will be scattered patches of sandy plains, low dunes till Jaisalmer.
Stop 1: Agolai Hills and Pediments
Agolai is a small town about 40 km west of Jodhpur, having hill - rocky/gravelly pediment - colluvial plain sequence on rhyolite (Fig. 17). A narrow shallow belt of palaeochannel can be seen as one approaches the town towards Jaisalmer. Dominantly because of rainfed situation, people of this region has adopted to conserving the meagre rainfall of few days in the ponds which they call the “nadi”. Runoff from the low rhyolite hillocks are collected in the nadi within no time (10 to 20 minutes) and the channels (~1 m deep and <1 m wide) dries off faster. However, people cultivate both deep (alluvial plains) and shallow gravel lands for major rainfed crops. It is interesting to see the water conservation structures as well as a shallow khadin at the distal end.

Stop 2: Balesar Sandstone Mines
At Balesar, the Jodhpur Sandstone is being quarried from the late 1970’s for use as building material (Fig. 18). The expansion of the quarries and dumping of rubbles on the adjacent plots have spoilt some marginal agricultural lands (Fig. 19). Adjacent to such mine areas one can see 20-45m high sand dunes and large interdune plains (Fig. 20). Almost all the high sand dunes are in parabolic form, occurring either as isolated parabolic or in chains of coalesced parabolic dunes. Weak segregation of CaCO3 within the dunes leads to formation of minor kanker nodules; silt and clay percentage varies from 2 to 6 percent only. In spite of natural stability the higher dunes are subjected to excessive pressure of cultivation, grazing and other form of exploitation. Result is high reactivation of the dunes, formation of mobile barchanoids along their slopes (Fig. 21).
Stop 3: Shetrawa Parabolic Dune - Stabilization
Shetrawa is a small town 36 km away from Balesar, and has a dominantly sandy landscape with rock outcrops and scattered desert trees (Fig. 22, 23). The sand dunes (parabolic type) are well vegetated, 20-30 m high and exhibit sand reactivated slopes and crest, situated on the left side of the NH 114. Attempt is on to check sand mobility from the dune fields using stabilization techniques like checker board pattern or parallel strips of locally available shrubs (Fig. 24).

Stop 4: Dechu Parabolic Dunes – Land use
Dechu is located 20 km away from Shetrawa on the Jaisalmer road. This is a major sandy upland area indicating much of the aeolian activity in the past. Dunes are 20-30 m high and possess well developed flanks (Fig. 25). Looking at the aspect of wind erosion activity and sand accumulation on the nearby highways, most of the sand dunes surrounding Dechu village area especially in the north, are under process of stabilization through tree plantation (Fig. 26).
Fig. 22. IRS-L3 FCC of dune landscape around Shetrawa.

Fig. 23. Google Earth view of stabilized and other sand dunes near Shetrawa.

Fig. 24. Field view of a sand dune at Shetrawa.

Fig. 25. Field view of a sand dune at Dechu.

Fig. 26. Sand dune stabilization through plantation near Dechu.
Stop 5: Lawan and Pokaran Playas
Distance between Lawan and Pokaran is 16 km. Geographically it has both rocky and saline landscape at an average elevation of 233m. The rocky tract is interspersed by number of playas or saline depressions, locally called ranns, with steep bounding rocky slopes, near Dediya, Lawan (Fig. 27, 28) and Pokaran (Fig. 29, 30). All these ranns were formerly connected through a stream. Soils are saline and so is the ground water. The pH is 7.6 at surface to 7.4 at 40-60 cm. Ec is 22.9-14.5 dS m-1. Other major landforms are: isolated hills, pediment, pediplain complex, hamada (high level rocky structural plains), gravelly pavements and barchans. Most numerous natural vegetation are Z. numularia, Caparis decidua, salvadoraoleoides. Lasiurus sindicus is the most dominant grass of the region, highly nutritive, therefore has high fodder value.

Fig. 27. Saline playa at Lawan.
Fig. 28. Google Earth view of the playa at Lawan.
Fig. 29. Saline playa at Pokaran.
Fig. 30. Satellite view of Pokaran playa and surroundings.
Stop 6: CAZRI Research Farm at Chandan
This is a village between Lathi and Jaisalmer, located about 20 km away from Lathi. This area can be best described as a barren sandy landscape which is suitable for rangeland development (Fig. 31, 32). The terrain is sculptured into rocky / gravelly plains, sand sheets and uplands in the form of linear and barchan dunes with complex formations. CAZRI has one of its research farms (under the Regional Research Station, Jaisalmer) that addresses the regional issues of grasslands / rangelands and crops under pressurized systems for this region (Fig. 33).

Fig. 31. Google Earth view of sandy plain having barchans at Chandan.

Fig. 32. Degraded grassland at Chandan.

Fig. 33. Lasiurus sindicus grass grown by CAZRI at Chandan.
Stop 7: Bhojka Gravel Pavement
On route from Chandan to Jaisalmer, one can see a different terrain with moderate uplands and depressions. Bhojka and Basanpir are two of the intermediate villages, within 15 km distance on the highway. The pebbles and cobbles are typical form of Bhojka gravels and are of research interest as origin of these sediments are said to have fluvial connection (Fig. 34). Soils are sandy at the surface and either sandy or loamy sand in subsoil, underlain at variable depth by weakly developed or moderately developed lime concretionary zone, or weathered rock or gravels/pebbles. The environment is similar to Chandan. Besides, this is the place of occurrences of extensive desert pavements, the surface having greater assemblage of rounded pebbles, cobbles and few haematitic gravels (Fig. 35). Such type of sediments can be linked to possible fluvial action during a wetter climate in this region.

Fig. 34.
Gravel pavement at Bhojka.

Fig. 35.
Rounded to sub-rounded pebbles at Bhojka.
Day 3: 14/11/2017  
Jaisalmer to Damodara, Kuldhara, Sam and back  
Stay at Jaisalmer.

Jaisalmer district is spread over 38401 sq. km area in the heart of Thar Desert in India, and is one of the largest districts whose area will be almost equal to one of the states, Kerala. There is no perennial river in the district, but few ephemeral and buried channels do exist. The underground water level is very low. The climate is extremely hot during summer with maximum temperature reaching up to 49.2 degree Celsius and extremely cold during winter with minimum temperature of 1 degree Celsius. Mean annual rainfall is 195 mm (Fig. 36). The terrain within a radius of about 40 km is stony and rocky. The area is barren, undulating with a number of landforms of aeolian, tectonic, lacustrine, fluvial origin with great variability. The traverse from Jaisalmer to Sam (about 45 km on the highway) will be a low undulating terrain (234 m at Jaisalmer to 179 m at Sam) with more of rocky plains with scattered appearances of low sand dunes. The hamada, cuesta, rock weathering and erosional features will be of interest to the geomorphologists. Finally, the rocky terrain will be cut short by an extensively formed sandy landscape at Sam (a linear dune field with barchan bedforms).

![Fig. 36. Rainfall at Jaisalmer.](image-url)
Stop 1: Jaisalmer Hamada
Jaisalmer region is also known as both rocky and sandy desert. While you are at Jaisalmer city, a rocky terrain comprising rocky plains, hamadas and desert pavement are in the immediate surroundings (Fig. 37). As one leaves Jaisalmer city towards Lodurva, one encounters first a steep escarpment and then climbs to the top of the rocky structural plains called Hamada on Jaisalmer Limestone (Fig. 38).

Stop 2: Damodara Hill slopes and pediment
The site, about 30 km to the west of Jaisalmer on the Sam route, is an assemblage low rocky upland having pediments and rocky plains (Fig. 39). One can also find some well-developed khadins nearby, once one descends the gentle slope of the hamada to the colluvial plain. Also surfaces and rock features show different stages of weathering and erosion.
Stop 3: Kuldhara, Ancient Settlement
About 15 km west of Jaisalmer lies the ruins of a village which was called Kuldhara. The village was established in 1291 A.D., by the Paliwal Brahmins. The first sight of Kuldhara village, more a town actually, sends one’s imagination running to the time it may have been inhabited (Fig. 40). A well-planned settlement, the straight and wide streets ran in grids with houses opening into them. All design elements kept both aesthetics and utility in mind. A kind of a garage opened into the streets to park carts in. Temples, step wells and other structures were all signs of sound development over the centuries.

Stop 4: Kanoi Sandy Plain
Kanoi is located 5 km further west on the Sam route after Damodara, and sand starts accumulating before we reach the Sam desert area. The terrain is dominantly rocky with low uplands, weathered morphology with occasional sand deposits (Fig. 41).

Stop 5: Sam Linear Dunes
Sam is a tourist place of national importance, about 45 km to the west of Jaisalmer. Because of its aeolian environment and peculiar dune fields, it is one of the must-see sites of Jaisalmer. The region receives annual rainfall of 180 mm and with rocky terrain and almost devoid of any vegetation, this is an ideal place for sand movement, deposition and dune formation (Fig. 42). The major dune systems are longitudinal type. Because of extreme arid situation, dunes become highly reactivated under slightest biotic pressure and start advancing as chains of...
barchanoids either atop the old forms or in newer areas. During 1978, Government of Rajasthan undertook a programme of stabilization of a part of one longitudinal dune at Sam with technical expertise of CAZRI. The mulching was done with locally available shrubs and grasses. A part of sand dune is left barren and has beautiful chains of barchanoids. This part has become tourist attraction and is known as the Sunset point of Sam. This is also the most mobile part of the dune engulfing newer areas each year.

Day 4: 15/11/2017
Jaisalmer to Baramsar, Mokal, Chhatrel, Rupsi, Lodurva, and to Jodhpur
Stay at Jodhpur.

Broadly the area between Jaisalmer, Mokal, Rupsi and Lodurva is dominantly rocky-gravelly, while the area towards Sam is dominantly sandy. The rocky limestone Hamada surface around Jaisalmer has many wind erosion features, as sand blasting on the softer limestone has cut through the rock (Fig. 43). Down the slope of the Hamada, the low-lying areas or depressions are utilized for runoff farming for winter crops under conserved moisture.

Stop 1: Baramsar Khadin on Pediment
On way to Mokal, which is about 30 km away from Jaisalmer, Baramsar is a small village located amidst a rocky terrain. The significant features are the number of water conservation structures, locally called Khadin, on the rocky pediment land. The structures represent people’s wisdom of conserving water received through rills and narrow but shallow channels emerging from nearly low rocky uplands (Fig. 44).
Stop 2: Mitha Rann (Playa)
This is a saline playa not suitable for cultivation, but often its margins are used for grazing. These ranns are partly oriented in the dominant SW wind, although a dry valley in the rocky terrain also links these depressions. Kar (1995) thought that strong wind erosion along zones of weakness in the softer limestone terrain and possible groundwater-related weathering could be associated with such rann formation at this place.

Stop 3: Mokal Cuesta and Pediment
Mokal is at a distance of 30km from Jaisalmer town. It is situated in the fringe of dunes and rocky uplands with some dry channels. The rocky landscape is dotted with hamada, rocky/gravelly pediments and pavements (Fig. 45). Interesting features include various rock weathering patterns and erosions due to wind erosion strength in the region.
Stop 4: Chhatrel Desert Weathering
Chatrail is another rocky upland with hamada nearby. Major landforms are few rock outcrops with dominance of desert pavement. The dry course of some channels are also of interest. One can observe various forms of physical and chemical weathering (Fig. 46, 47).

Stop 5: Rupsi Khadin Cultivation
Khadin is a local system of rainwater conservation, and it preserves the soil moisture in the land to be utilized for agriculture, mainly during winter. Runoff harvested in low-lying areas from the surrounding rocky catchments for practicing agriculture has great significance in this rocky area. In some cases the runoff water is diverted through small channels to farm lands in lower reaches. Bunds constructed across the slope and farm lands lying between the ridges of the catchment are normally inundated with water during monsoon period, but on drying the rabi crops are sown. During drought years, such fields are put under kharif crops. About 84 khadins have now been constructed by the Irrigation Department, Government of Rajasthan. The catchment areas of these khadins vary from 2.5 to 51.0 sq. km, with storage capacity ranging from 0.028 to 2.33 mcm. Some of them are privately owned khadins, constructed by cultivators on their farms. This practice of water harvesting on farmland is thus gaining popularity in the district. One such big khadin is at Rupsi (Fig. 48, 49). According to historical records, the Paliwal clan who resided here in the 15-16th century A.D, developed and perfected this technique.
Stop 6: Ludarva Temple Architecture
Lodurruva, the ancient capital of Jaisalmer, is located along the left bank of a gravelly ephemeral stream named the Kankni Nala. Although in ruins, the site has an old, richly-carved and decorated Jain temple, which has been renovated for its historical and religious importance. The temple shows the skill of local craftsmen in the use of available stones in making architectural beauties (Fig. 50).

Fig. 50.
Jain temple at Lodurva.

Day 5: 16/11/2017
Jodhpur to New Delhi by Flight
Stay at New Delhi.
References


Attri, S.D. and Tyagi, A. 2010. Climate Profile of India. India Meteorological Department, New Delhi, 122p.


